Energy Conversion and Management 164 (2018) 144–156

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Technical, economic and environmental optimization of combined heat and power systems based on solid oxide fuel cell for a greenhouse case study

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ARTICLE INFO

Keywords:
Solid oxide fuel cell (SOFC)
Combined heat and power (CHP)
Multi-objective optimization
Levelized cost of Energy (LCOE)
CO_2 emission

ABSTRACT

The aim of this paper is to investigate the application of solid oxide fuel cell (SOFC) as the prime mover of a combined heat and power (CHP) system. In this paper, four hybrid systems are proposed to improve the performance of CHP and compare with baseline condition. Capacity design and operation strategy of hybrid systems are applied to a case study of a greenhouse located in Mahabad, Iran and optimized by using technical, economic and environmental objective functions. Levelized cost of energy (LCOE) and CO_2 emission rate are considered as the objective functions. For LCOE optimization, three scenarios are considered to evaluate the impacts of future energy prices and CO_2 tax. In scenario *i* (Regional energy prices in Iran without CO_2 tax), none of the proposed hybrid systems are competitive with the baseline case and the difference between LCOEs of the best hybrid system and baseline is 2.8 ¢/kWh. In scenario *ii* (Regional energy prices in Iran with CO_2 tax), although the difference between LCOEs decreases to 1.8 ¢/kWh, none of the proposed hybrid systems are beneficial in comparison with the baseline. In Scenario *iii* (world average energy prices with CO_2 tax), in contrast with previous scenarios, optimized LCOEs of two hybrid systems (11.15 and 11.4 ¢/kWh) are lower than baseline LCOE (17.56 ¢/kWh). From CO_2 emission point of view, all of the proposed optimized hybrid systems have lower CO_2 emission than baseline. Finally, a multi-objective optimization is done to consider both techno-economic and environmental objective functions simultaneously and provide a powerful decision support tool. The results show that yearly CO_2 emission of SOFC base CHP hybrid systems are averagely 62% lower than conventional systems. Moreover, they would be economically beneficial in the case of increasing energy prices and environmental limitations.

1. Introduction

Nowadays, the dominant challenge for all countries is energy sustainability or energy for sustainable development [1–3]. Although achieving sustainable development has interested lots of researchers, human high dependency on nonrenewable energy sources cannot be stable in the long-term [4,5]. It happens while energy efficiency of conventional energy conversion technologies is low [6]. Low efficiency of energy technologies will lead to more environmental pollution, fuel consumption and operational costs [7]. Such problems are against the indexes of sustainable development [8]. The basic strategies to increase the sustainability of energy supply systems are (*i*) the selection of energy conversion technology with high efficiency such as Solid Oxide Fuel Cells (SOFCs) [9], (*ii*) integration of energy conversion technologies [10], (*iii*) use them in cogeneration systems [11,12] and (*iv*) optimal design and operation of energy systems [13].

Solid Oxide Fuel Cell (SOFC) with the efficiency of 40–60%, is considered as one of the most efficient energy conversion technologies [14]. High operational temperature of SOFCs has made it possible to use different fuels such as natural gas directly [15–18]. Sui and Xiu [19] investigated a range of possible and practical fuel kinds in SOFC applications. They were of the opinion that the most agreeable feature of SOFCs is their fuel flexibility at high efficiency. Ozcan and Dincer [20] and Minguela et al. [21] analyzed the performance of SOFC systems which are fed by different gaseous fuels from biomass gasification and different sources.

Integration of SOFC with other conventional technologies such as gas turbine [22,23] to form a hybrid power system is known as an applicable method to increase the energy efficiency of the whole system [24–26]. Chan et al. [27] and Saebea et al. [28] reported hybrid systems of SOFC/GT with electrical efficiency in the range of 60–65%. As it is specified, the efficiency of the hybrid SOFC/GT system was about 20–25% more than conventional energy systems such as gas turbine or combined cycle power plant. Barelli et al. [29] introduced a SOFC/GT hybrid system that could be an attractive solution for μ-grids power range. Bakalis and Stamatis [30] and Hajabdollahi and Fu [31]

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https://doi.org/10.1016/j.enconman.2018.02.023
Received 22 December 2017; Received in revised form 3 February 2018; Accepted 5 February 2018
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Nomenclature

A	area, m^2
A_{opt}	area of the active TPB regions, m^2
C	investment cost, \$/kW
D_p	average diameter of the pore, m
D_w	width of a corrugation, m
E	activation energy, $J{\cdot}mol^{-1}$
En	annual energy consumption
F	Faraday's constant, $C\,equiv^{-1}$
H	enthalpy, $J\,mol^{-1}$
i	current density, $A{\cdot}m^{-2}$
i_0	exchange current density, $A{\cdot}m^{-2}$
I	working current, A
In	investment cost, \$
K	equilibrium constant
L	length, m
L_{opt}	active TPB region thickness, m
$LCOE$	levelized cost of electricity, ¢/kWh
m	mass flow rate, kg/s
M	molecular weight, $kg\,mol^{-1}$
n	equivalent electron per mole of reactant, $equiv{\cdot}mol^{-1}$
n_{ch}	number of channels
Op	operation cost, \$/year
P	pressure, Pa
Q	heat transfer, J
r	discount rate
R	universal gas constant, $J\,mol^{-1}\,K^{-1}$
$S°$	standard entropy, $J\,mol^{-1}\,K^{-1}$
SCR	steam to carbon ratio
T	temperature, K
T_{max}	maximum temperature, K
V	voltage, V
x	respective molar rate of reforming reaction
X	molar fraction of component in the mixture
y	respective molar rate of shift reaction
z	respective molar rate of electrochemical reaction

Greek symbols

α	fraction of the reaction heat that is generated at the anode
β	ohmic resistance, Ω
δ	pre-exponential factor, $\Omega^{-1}{\cdot}m^{-2}$
φ	porosity
η	voltage losses, V
ν	diffusion volume of simple molecules, cm^3
σ	electrical conductivity, $\Omega^{-1}\,m^{-1}$
ψ	tortuosity

Subscript and super script

act	activation
c	compressor
cc	combustion chamber
conc	concentration
ec	economizer
ev	evaporator
f	fuel
g	gas
is	isentropic
OCV	open circuit voltage
ohm	ohmic
LMTD	logarithmic average of the temperature
n	useful life, year
r	compression ratio
sh	Team heater
st	steam
t	turbine
x	x direction
y	y direction
z	z direction

increased the efficiency of hybrid SOFC/GT system by optimizing the design of system components.

Besides the high efficiency of SOFCs and their ability to integrate with other conventional technologies, they also can be used in combined generation systems [32]. Combined heat and power (CHP) systems are able to decrease the operational costs, environmental pollution and consumption of primary forms of energy [33]. In recent years, a lot of research has been done to introduce fuel cells as a substitute for conventional energy conversion technologies [34]. Pirkandi et al. [35] presented a complete model of combined power and hot water production system based on SOFC. The result of their work showed that the efficiency of system was 73%. Naimaster and Sleiti [32] presented a SOFC-based CHP system for office building and indicated that using this system, comparing to common air conditioning systems, will decrease 14.50% of annual energy consumption and 62% of CO_2 production. Napoly et al. [36] and Jing et al. [37,38] investigated the economic and environmental benefits of SOFC based CCHP systems application in residential buildings while Giarola et al. [39] analyzed the competitive ability of SOFC based CHP with conventional alternatives in industrial scale. Ma et al. [40] and Khani et al. [41] proposed a power/cooling cogeneration system based on SOFC/GT and performed a detailed analysis. Results showed that the technical and economic performance of SOFC/GT system is more efficient than stand-alone SOFC.

The literature demonstrates that although CHP systems are able to decrease operational costs, pollution and fuel consumption, the application of CHP systems has some limitations. One of the most significant problems of combined production systems is inconsistency of produced heat and power with heating and power demand [42]. As the excess power could be sold to the grid, the rate of produced power is not restricted. However, if the produced heat exceeds demand, the operation of hybrid system should be stopped otherwise the excess heat will be wasted. Kialashaki [43] proposed a model for determining an optimal strategy to design of the CHP systems. Delattin et al. [44] suggested steam injection gas turbine (STIG) as a solution for excess heat problem which is produced by CHP. They used excess heat in hot seasons to produce steam and injected produced steam into STIG. They showed that by injecting 3.3% water, the electric efficiency can be risen by 5.1%.

The aforementioned literature confirms that the application of SOFC as the prime mover of CHP systems has numerous sustainable advantages such as higher efficiency, lower emission and more economic justification than traditional energy conversion technologies. The question that the present work tries to answer is finding the optimum hybrid system which is the best option for improving SOFC based CHP and analyzing its advantages and disadvantages in comparison with baseline condition.

In this paper, four SOFC based hybrid systems are proposed to improve the performance of CHP. Capacity design and operation strategy of hybrid systems are applied to a case study of a greenhouse situated in Mahabad, Iran and optimized by using technical, economic and environmental objective functions. In summary, the followings are the main contributions of this paper into the subject:

- Technical, economic and environmental modeling, analysis and

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