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Thermo-economic modeling of an atmospheric SOFC/CHP cycle: an exergy based approach

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Abstract – Sustainability is one of the challenging issues in electricity production systems. Recently, solid oxide fuel cell (SOFC) has been suggested for use in combined heat and power (CHP) systems. This application is introduced as a promising environmentally-friendly system according to the thermodynamic and electrochemical models. In this paper, an atmospheric SOFC/CHP cycle was analysed based on integrating exergy concepts, energy and mass balance equations. In this regard, a zero-dimensional energy and mass balance model was developed in engineering equation solver (EES) software. Two dimensionless parameters (the exergetic performance coefficient (EPC) for investigating the whole cycle, and exergetic efficiency for investigating the exergy efficiency of the main component of this cycle) were applied. Results show that efficiencies of the system have been increased substantially. The electrical efficiency, total efficiency and EPC of this cycle were ∼54%, ∼79% and ∼58% respectively. Moreover, the CO_2 emission is 19% lower than when compared with a conventional combined power cycle fed by natural gas. In addition, a dynamic economic evaluation was performed to extract the most sensitive parameters affecting the outputs: electricity sales price (ESP), equipment purchase cost and fuel cost. Furthermore, an electricity production cost of ∼125 \$ MW.h^{-1} was attributed to our model, resulting in yet further cost reduction for widespread applications of this cycle.

Key words: SOFC / CHP / exergy efficiency / thermo-economic / EPC

1 Introduction

Power generation is essential and the current global trend shows increasing demand. Based on the proven advantages such as high electrical efficiency, high power density, low pollution and noise production the SOFC technology is suggested as a promising eco-friendly alternative in power generation systems [1]. SOFC can operate with various kinds of fuels such as natural gas, carbon monoxide, methanol, ethanol and hydrocarbon compounds, which facilitates a wide range of applications [2]. Due to the relatively high operational temperature (800−1000 °C), this technology appears more appropriate for integration with CHP systems applications, thus developing distributed generation systems, increasing overall plant efficiency and leading to a clean cycle [3].

Farhad et al. [4] investigated the performance of a biogas fuelled SOFC/MCHP system thorough a numerical simulation. They achieved a parametric analysis of three configurations including anode recirculation, steam reforming and partial oxidation. Their results confirmed that the net AC electrical efficiency attainable for these configurations was around 42.4%, 41.7% and 33.9% respectively. Staffell [5] conducted an economic feasibility study in domestic applications based on the use of SOFC technology in CHP systems, with positive results. Kuramochi [6] performed an economic feasibility study of SOFC/CHP cycles for market penetration by considering environmental constraints in the energy market. The results showed that SOFC/CHP without CO_2 capture requires a low SOFC total production cost of about 310 \$ kW^{-1} to compete with conventional GE/CHP. Meanwhile, SOFC/CHP with CO_2 capture using an air separation unit (large scale type) can compete with GE/CHP at higher stack production costs when the CO_2 price is above 37 \$ tCO_2^{-1}.

Nanaeda et al. [7] studied the dynamic modelling of SOFC/CHP cycles in various operational conditions and their connections to the national power grid. Analytical

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Nomenclature

V_{act}	Activation polarization	*Greek symbols*	
U_{a}	Air utilization factor	η	Efficiency
A	Area (m^2)	y_i	Mole fraction
A_{act}	Cell active area (m^2)	ε	Recuperator effectiveness
i	Cell current density (A.m^{-2})	*Abbreviation*	
V	Cell voltage (V)	A.B	After Burner
V_{con}	Concentration polarization	CAPEX	Capital Expenditure
C	Cost ($)	CHP	Combined Heat and Power
P_{SOFC}	DC SOFC power (kW)	DHW	Domestic Hot Water
$Kp_{\mathrm{r,s}}$	Reforming, Shifting equilibrium constant	Eco	Economizer
$\dot{E}x$	Exergy (kW)	EES	Engineering Equation Solver
F	Faraday constant (96 485 As mol^{-1})	EPC	Exergetic Performance Coefficient
U_f	Fuel utilization factor	ESP	Electricity Sales Price
$\dot{n}$	H_2 reacted moles (mol.s^{-1})	GE	Gas Engine
$\dot{Q}$	Heat (kW)	HPR	Heat to Power Ratio
LHV	Lower heating value (kJ.mol^{-1})	IR	Internal Reformer
$\dot{m}$	Mass flow rate (g.s^{-1})	MCHP	Micro CHP
$\dot{n}_i$	Molar flow rate (mol.s^{-1})	OPEX	Operational Expenditure
E_{re}	Nernst voltage (V)	SOFC	Solid Oxide Fuel Cell
N_{cell}	Number of cells	IRR	Internal Rate of Return
V_{ohm}	Ohmic polarization	*Subscripts and Superscripts*	
DT_{p}	Pinch point temperature difference (K)	an	Anode
$\dot{W}$	Power (kW)	aux	Auxiliary
$V_{\mathrm{P.R}}$	Pre-reformer volume (m^3)	ca	Cathode
P	Pressure (bar)	ch	Chemical
nl	Project life time (yr)	inv	DC/AC inverter
ex	Specific exergy	D	Destruction
h	Specific molar enthalpy (kJ.kmol^{-1})	Out	Outlet
s	Specific molar entropy (kJ.(kmol.K)$^{-1}$)	ph	Physical
SCR	Steam to carbon ratio	rec	Recuperator
T	Temperature (K)	0	Reference condition
R_{u}	Universal gas constant (kJ.(kmol.K)$^{-1}$)	t	Total

results indicated that with a 13.1% average increase in ESP, the system can provide the grid with a 50% operating range of dispatchable urban power at an overall thermal efficiency of 80%.

It should be noted that the afore mentioned studies focused just on thermodynamic and/or thermo-economic analyses based on energy balance, and less attention has been paid to the concept of useful work (exergy) in those papers and in other studies [8–16].

In this paper, the exergetic analyses were carried out for all pieces of equipment after introducing two new parameters: the equipment exergetic efficiency and EPC. To meet this requirement, the SOFC/CHP cycle was modelled in the open source code of EES software, and equations for mass and energy balance, electrochemical and exergy were solved simultaneously. Our proposed model was then validated with the data reported in previous research. The final stage in our thermo-economic model was a dynamic economic study based on the dominant direct and indirect costs. A one-way sensitivity analysis was applied to determine the most influential parameter for decision making and facilitating widespread application of this system.

2 Cycle description

Figure 1 shows a schematic view of the SOFC module and CHP module in this study. Methane fuel enters the blower from stream 1 and mixes with anode recirculation depleted fuel before entering the pre-reformer and finally entering the SOFC's anode. As shown, air enters the cycle from stream 8 and after leaving the blower, is preheated in the recuperator, finally entering the SOFC's cathode. In the after burner, some of the fuel exiting from the anode burns with depleted air from the cathode (stream 12). After preheating the input air in the recuperator, the flue gases pass through the economizer

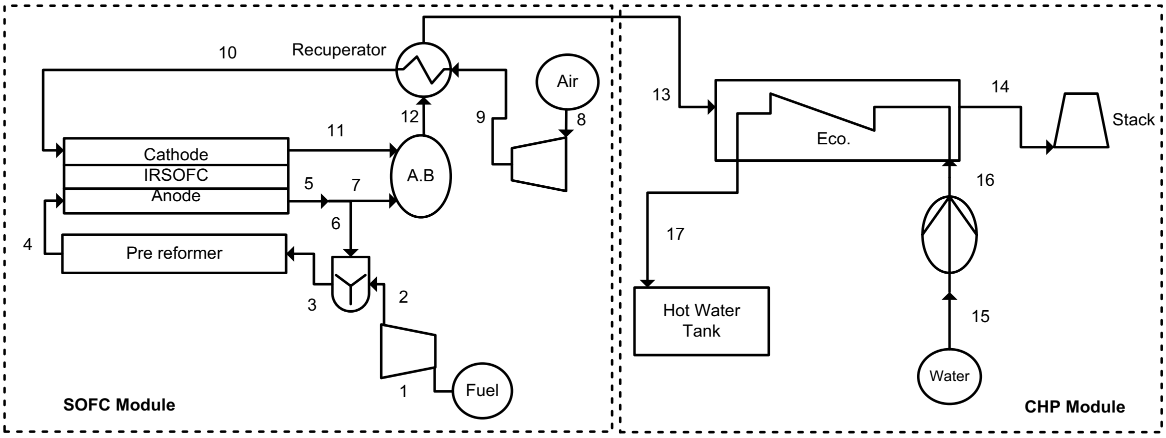

Fig. 1. A schematic view of a methane-fuelled SOFC/CHP system with internal reformer and anode off-gas recirculation.

(stream 13) with sufficient temperature to supply the energy for hot water applications such as space heating or domestic applications.

3 Modeling methodology

The principle concept of the SOFC module is converting the chemical energy of fuel directly into electrical energy. This objective is achieved through a series of electrochemical reactions [17]. The main application of the CHP module in power generation systems is producing hot water by using the excess heat of the after burner exhaust stream.

These two systems were integrated in our proposed model, which was developed based on the following assumptions:

1- System components are taken as a lumped control volume.
2- Equipment is issued in steady state conditions.
3- All chemical reactions reach equilibrium.
4- All gases are ideal gases.

To begin with, a zero-dimensional thermodynamic model of steady state flow was developed to simulate the system by using mass and energy balance equations. This computational model determined molar flow values ($\dot{n}_i$), mole fractions (y_i) and also physical properties such as enthalpy and entropy of all addressed streams shown in Figure 1. In order to keep continuity, output parameters from a piece of equipment were considered as input parameters to the next one. Table 1 shows all of the governing equations in this study.

3.1 Exergy modeling

In exergy modelling, the location and amount of exergy losses are determined in a target energy system. The system efficiency will increase by reducing energy losses, leading to an ideal state. The purpose of this analysis is to identify the location, type and amount of entropy during variations, and also to determine the effective factors of these irreversibilities. This procedure will shed more light on available effective alternatives to increase system efficiency.

The specific total exergy (ex) includes four components. When surface tension, magnetic and electrical effects are negligible, the specific total energy can be obtained from equation (3-a). Equation (3-b) can be derived for the physical exergy at the cycle if we assume the potential and kinetic exergies are negligible. The chemical exergy of an ideal mixture of N ideal gases is obtained according to equation (3-c). The ex_k^{CH} is the standard molar chemical exergy for substance k, assuming the ambient temperature is T_0 and y_k is mole fraction of the substance k at temperature T_0 [18]. In each control volume, the exergy destruction rate is calculated according to equation (3-d). Afterward, the total exergy destruction in the cycle is provided by equation (3-e). For another point of view, exergy efficiency in each piece of equipment expresses the entropy generation and is calculated by using equation (3-f). The EPC is a concept as it presents a holistic evaluation of the exergetic patterns. Equation (3-g) was used to determine EPC.

3.2 SOFC module modeling

The SOFC module includes the fuel blower, mixer, pre-reformer, ejector, tubular SOFC stack and AC-DC inverter. All of the design parameter and technical specifications in this module are based on [19].

The methane is used as input fuel, entering the fuel blower (stream 1) where it is mixed with depleted recirculation fuel coming back from the anode side (stream 6) at the mixer. Output fuel from the anode includes more steam and extra heat energy for the fuel reforming process, so part of it is returned by an ejector and is added to the input fuel. The amount of returned fuel can be estimated with equation (4), according to the steam to carbon ratio, which is strongly related to the anode

Table 1. List of equations in this model.

Description (equipment)	Equation	No.
Mass balance	$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}}$	(1)
Energy balance	$\sum \dot{Q}_{\text{in}} + \sum \dot{W}_{\text{in}} + \sum \dot{n}_{\text{in}} h_{\text{in}} = \sum \dot{Q}_{\text{out}} + \sum \dot{W}_{\text{out}} + \sum \dot{n}_{\text{out}} h_{\text{out}}$	(2)
Specific exergy	$ex = ex^{\text{PH}} + ex^{\text{ke}} + ex^{\text{pe}} + ex^{\text{ch}}$	(3-a)
Physical exergy	$ex^{\text{PH}} = (h - h_0) - T_0(s - s_0)$	(3-b)
Chemical exergy	$ex^{\text{ch}} = \sum y_{\text{k}} ex_{\text{k}}^{\text{CH}} + R_{\text{u}} T_0 \sum y_k \ln y_k$	(3-c)
Exergy destruction	$\dot{E}x_{\text{D}} = \sum_j \dot{Q}_j \left(1 - \frac{T_0}{T_j}\right) - \dot{W} + \sum_i (\dot{E}x_i)_{\text{in}} - \sum_i (\dot{E}x_i)_{\text{out}}$	(3-d)
Total exergy destruction	$\dot{E}x_{\text{D,total}} = \sum_i \dot{E}x_{\text{D},i}$	(3-e)
Exergetic efficiency, equipment order i	$EEf_i = \left(1 - \frac{\dot{E}x_{\text{D},i}}{\dot{E}x_{\text{in},i}}\right) \times 100$	(3-f)
EPC of cycle	$EPC = \left(1 - \frac{\dot{E}x_{\text{D,total}}}{\dot{E}x_{\text{fuel, in}}}\right) \times 100$	(3-g)
Steam to carbon ratio (pre-reformer)	$SCR = \frac{\dot{n}_{3,H_2O}}{\dot{n}_{3,CH_4}}$	(4)
Reforming process (Pre-reformer & SOFC)	$CH_4 + H_2O \rightarrow CO + 3H_2$	(5)
Shifting process (Pre-reformer & SOFC)	$CO + H_2O \rightarrow CO_2 + H_2$	(6)
Process equilibrium of reforming process	$Kp_{\text{r}} = \frac{p_{H_2}^3 p_{CO}}{p_{CH_4} p_{H_2O}}$	(7)
Process equilibrium of shifting process	$Kp_{\text{s}} = \frac{p_{H_2} p_{CO_2}}{p_{CO} p_{H_2O}}$	(8)
Electrochemical process (SOFC)	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	(9)
Utilization factor (SOFC)	$\text{U}_{\text{f}} = \frac{\dot{n}}{4\dot{n}_{1,CH_4}}$	(10)
Means of the recuperator effectiveness	$\varepsilon_{\text{rec1}} = \frac{T_{10} - T_9}{T_{12} - T_9}$	(11)
Cell voltage (SOFC)	$V = E_{\text{re}} - V_{\text{act}} - V_{\text{ohm}} - V_{\text{con}}$	(12)
SOFC power	$\text{P}_{\text{SOFC}} = \frac{N_{\text{cell}} \times V \times i \times \text{A}_{\text{act}}}{1000}$	(13)
SOFC output power	$\dot{W}_{\text{SOFC}} = \eta_{\text{inv}} P_{\text{SOFC}}$	(14)
Minimum temperature difference	$T_{14} = T_{17} + DT_{\text{p}}$	(15)
Economizer energy balance	$\dot{n}_{13} h_{13} + \dot{n}_{16} h_{16} - (\dot{n}_{14} h_{14} + \dot{n}_{17} h_{17}) = 0$	(16)
Electrical efficiency	$\eta_{\text{ele}} = \frac{\dot{W}_{\text{net}}}{\dot{n}_{CH_4} LHV}$	(17)
Total efficiency	$\eta_{\text{t}} = \frac{\dot{W}_{\text{net}} + \dot{Q}_{\text{CHP}}}{\dot{n}_{CH_4} LHV}$	(18)

Table 2. System component purchase cost data summary.

Equipment	Cost model equation	No.
SOFC [22]	$C_{\mathrm{SOFC}}{=}A_{\mathrm{act}}N_{\mathrm{cell}}(2.96.T_{\mathrm{SOFC}}-1907)$	(19)
Inverter [22]	$C_{\mathrm{inv}}=10^5\times\left(\frac{\dot{W}_{\mathrm{SOFC}}}{500}\right)^{0.7}$	(20)
Blower (air & fuel) [22]	$C_{\mathrm{blower}}=91562\left(\frac{\dot{W}_{\mathrm{blower}}}{445}\right)^{0.67}$	(21)
Pre-reformer [23]	$C_{\mathrm{P.R}}=130\left(\frac{A_{\mathrm{P.R}}}{0.093}\right)^{0.78}+3240V_{\mathrm{P.R}}^{0.4}+21280.5V_{\mathrm{P.R}}$	(22)
SOFC auxiliary equipment [22]	$C_{\mathrm{aux}}=0.1\times C_{\mathrm{SOFC}}$	(23)
HRSG [22]	$C_{\mathrm{HRSG}}{=}\,8600+670(A_{\mathrm{HRSG}})^{0.83}$	(24)
Recuperator [22]	$C_{\mathrm{Recuperator}}{=}\,130(A_{\mathrm{Recuperator}}/0.093)^{0.78}$	(25)

recirculation process. For proper operation of the pre-reformer system, the steam to carbon ratio (identified a non dimensional ratio) is usually assumed between 2 and 3 as a constant [20].

Output fuel from the mixer (stream 3) enters the pre-reformer where reforming and shifting reactions occur as mentioned in equations (5) and (6). In relation to this, part of the inlet methane and carbon monoxide are converted to hydrogen. As a statement and to ensure completion for reactions, the equilibrium temperature is considered equal to the outlet temperature from the pre-reformer (T_4) [19]. The amounts of reformed methane and shifted carbon monoxide are determined using the equilibrium constant equations (7) and (8). The required heat of this section is provided by the SOFC fuel cell stack. The equilibrium constants and thermal functions Kp_r and Kp_s are deterministic and temperature dependent [20].

Gases leaving the pre-reformer enter the internal reformer SOFC stack and the reactions of equations (5), (6) and (9) occur simultaneously. It is theoretically assumed that the whole input methane to the SOFC is reformed and off-gases are methane free. The molar rate of the consuming hydrogen is determined by the utilization factor presented in equation (10).

There is a complexity to converge the equation with iterative procedures in modelling, which is the overall cycle dependency related to unknown initial composition of anode off-gas.

The recuperator effectiveness ($\varepsilon_{\mathrm{rec}}$) is calculated by equation (11).

The SOFC module voltage is calculated according to equation (12). In this equation the E_{re} is determined by the nernst equation, where as the V_{act}, is obtained using the butler-volmer equation. V_{ohm} is evaluated by using an equation concerning thermal resistance in the anode, cathode, electrodes and inter-connector. In addition, V_{con} is determined based on voltage drops according to an approach in [21]. Finally, inserted cell voltage relating to equation (13) and (14) will clear the exact amount of power (DC or AC type) of the SOFC module.

3.3 CHP module modeling

The CHP module is an important part of the system affecting the characteristics of the overall cycle. The recuperator's exhaust gas flow has enough energy to supply the required energy for hot water demand. This module includes an economizer, circulation pump and hot water reservoir. In CHP systems, water is pumped to the required head and then, in the economizer, is heated to the desirable temperature (90 °C) by the hot gas flow. DT_p is the minimum pinch point temperature difference which is utilized by equation (15). Then, the flow rate of hot water production can be determined based on energy balance equation (16).

3.4 Economic modeling

Economic modelling takes place using a time-bounded dynamic model and equipment cost functions. The main considered equipments, are the SOFC stack and auxiliaries, DC/AC inverter, blowers, recuperator, pre-reformer and CHP module. The equipment purchase cost functions are presented in Table 2 (Eqs. (19) to (25)). The total summation of the direct costs (e.g. landscaping, installation, instrumentation, piping etc.) and indirect costs (constructions, engineering and etc.) along with investment costs are considered as *CAPEX*. The other terms, like energy and production costs, are considered as *OPEX*.

For further explanation, the incomes should be considered in two categories, namely ESP and saved energy in the CHP module.

3.5 Initial input parameter

Table 3 shows the initial input parameters in the proposed model.

Table 3. The initial input parameters of this SOFC/CHP system.

Parameter	Value	Parameter	Value
Reference condition		SOFC module	
Reference temperature (K)	298.15	Air utilization factor	0.20
Reference pressure (bar)	1.013	Fuel utilization factor	0.85
CHP module		SCR	3
Minimum temperature difference (K)	20	Average current density ($A.m^{-2}$)	3200
Economizer pressure loss (%)	5	SOFC pressure loss (%)	2
DHW temperature (K)	363.15	Number of cells	1152
COST model		Cell active area (m^2)	0.0834
Interest rate (%)	12	DC/AC inverter efficiency (%)	96
Fuel price ($ $kg.methane^{-1}$)	0.2585	Air & fuel blowers' efficiency (%)	85
Annually operation time (h.r)	8760	Recuperator pressure loss (%)	2
Life cycle time (yr)	10	Recuperator effectiveness (%)	84
Electricity sale price ($ $MW.h^{-1}$)	117.84		
Boiler efficiency (%)	0.85		

4 Results and discussion

4.1 Modeling process and results

The modelling results at different points of the cycle are presented in Table 4. It should be noted that the rendered values in Table 4 are concluded based on the input parameters of Table 3. Other key features of the cycle and economic calculations are presented in Table 5.

According to these results, the electrical and overall efficiencies of this cycle reach 54.77% and 78.97% respectively, a range on par with the aforementioned studies [1, 9, 11, 12, 15, 17, 23]. The results also confirm the relatively high contribution of the SOFC stack and auxiliaries cost to the total investment. Consequently, any successful attempt to moderate those costs could lead to the widespread application of this system. In the current model, the electricity production cost is equal to 125.5 $ $MW.h^{-1}$, which is 6% higher than normal electricity production cost 117.84 $ $MW.h^{-1}$ (Key World Energy Statistics, 2012).

According to Table 4, the rate of CO_2 production in this system is 20.68 $g.s^{-1}$, resulting in the discharge of 52.16 $tCO_2\,yr^{-1}$ to the atmosphere. Thus the specific CO_2 production of this system is 360.50 $g.kW.h^{-1}$, compared with the conventional gas fuelled combined power plants (large scale CHP systems) that generate 446 $g.kW.h^{-1}$ CO_2 [24], the present cycle show a reduction of 19.17% in CO_2 emissions. This leads to a conflict of interests between the sustainability and environmental aspects, and the excess cost of produced electricity in comparison with conventional power systems [25].

In order to promote the analysis focused on exergy terms, this research carries out two non-dimensional variables (named equipment exergetic efficiencies and cycle EPC), leading to the SOFC/CHP modelling of exergetic results and details presented in Table 6. The findings show that due to their high temperature loss, the recuperator and economizer have the most exergy destruction, highlighting the need for better cycle designs to degrade the temperature differences with in technical limitations. In other words, use of a low efficiency recuperator seriously decreases the electrical and overall efficiencies; thus, whilst use of an efficient recuperator and cleaning of the active heating area is recommended based on the presented model. The next reduction priorities related to exergy destructions are attributed to SOFC, due to the electrochemical reactions and after burner, due to the combustion process. As presented in Table 6, the total exergy destruction is 164.8 kW, which is proportionately large considering that we produce a net output power of 206.5 kW. Further studies based on power and efficiencies within exergy considerations to find better bounds of variations for mentioned terms seem necessary. To this end, the next step is parametric studies.

4.2 Parametric study

Generally, the input parameters are associated with uncertainties in real conditions. The electric power generation systems are not exceptional and input parameters can change over time due to unexpected reasons.

Table 4. Characteristics of SOFC/CHP system at each stream for nominal condition.

Streams	T (K)	P (bar)	$\dot{m}$ (g.s^{-1})	$\dot{E}x$ (kW)	Molar fraction (%)						
					CH_4	CO	CO_2	H_2	H_2O	N_2	O_2
1	298.15	1.01	7.52	393.2	100.00	–	–	–	–	–	–
2	298.15	1.32	7.52	393.5	100.00	–	–	–	–	–	–
3	1065.72	1.29	68.79	597.6	15.26	6.22	22.02	10.73	45.77	–	–
4	850.00	1.29	68.79	617.3	4.84	12.86	18.87	33.29	30.14	–	–
5	1242.49	1.26	94.35	325.4	–	7.34	25.99	12.66	54.01	–	–
6	1242.49	1.26	61.27	211.3	–	7.34	25.99	12.66	54.01	–	–
7	1242.49	1.26	33.09	114.1	–	7.34	25.99	12.66	54.01	–	–
8	298.15	1.01	548.65	2.4	–	–	–	–	–	79.00	21.00
9	298.15	1.32	548.65	14.8	–	–	–	–	–	79.00	21.00
10	1173.00	1.29	548.65	297.4	–	–	–	–	–	79.00	21.00
11	1242.49	1.26	523.08	316.0	–	–	–	–	–	82.46	17.54
12	1341.66	1.24	556.17	403.6	–	–	2.41	–	4.82	77.10	15.67
13	537.71	1.21	556.17	54.6	–	–	2.41	–	4.82	77.10	15.67
14	383.15	1.17	556.17	21.0	–	–	2.41	–	4.82	77.10	15.67
15	288.00	1.01	290.66	189.3	–	–	–	–	100.00	–	–
16	288.20	1.08	290.66	189.3	–	–	–	–	100.00	–	–
17	363.15	1.03	290.66	196.6	–	–	–	–	100.00	–	–

Table 5. Technical and cost characteristic results of SOFC/CHP system modelling.

Technical data		Cost data	
SOFC DC power (kW)	231.6	**CAPEX ($)**	**555 613**
SOFC AC power (kW)	222.4	Direct cost	*457 995*
Economizer duty (kW)	91.27	Equipment cost ($)	327 139
Air blower power (kW)	15.24	SOFC cost ($)	170 130
Fuel blower power (kW)	0.37	DC/AC inverter cost ($)	56 712
Net output power (kW)	206.5	Pre-reformer cost ($)	55 400
Electrical efficiency (%)	54.77	SOFC auxiliary cost ($)	17 013
Total efficiency (%)	78.97	Economizer cost ($)	11 601
EPC of cycle (%)	58.08	Air blower cost ($)	9546
		Recuperator cost ($)	5937
Voltage (V)	0.75	Fuel blower cost ($)	800
HPR	0.44	Indirect cost	*97 618*
Annual electricity production (GWh)	1.81	**OPEX ($)**	**128 739**
		Total annual cost ($)	227 074
		IRR (%)	12.88
		Electricity production cost ($ MW.h^{-1})	125.5
		Specific power cost ($ W^{-1})	2.69

In this regard we achieved a series of on-way sensitivity analysis for all factors. The result shows that U_f is the most influential on the performance efficiency of this system. Figures 2a and 2b show the results.

Figure 2a shows the effect of small changes of U_f on economic power, SOFC power, Heat to Power Ratio (*HPR)* and total exergy destruction. According to these results an increase in U_f causes an increase in SOFC power, an exergetic performance coefficient. On the other hand, it leads to a decrease in *HPR*, economic power, total exergy destruction, total efficiency and cell voltage.

Actually, an increase in U_f is attributable to an increase in SOFC fuel consumption which increases the SOFC power, the energetic performance coefficient and electrical efficiency. But it increases the irreversibility in the system (i.e. cell voltage drop). However, an increase

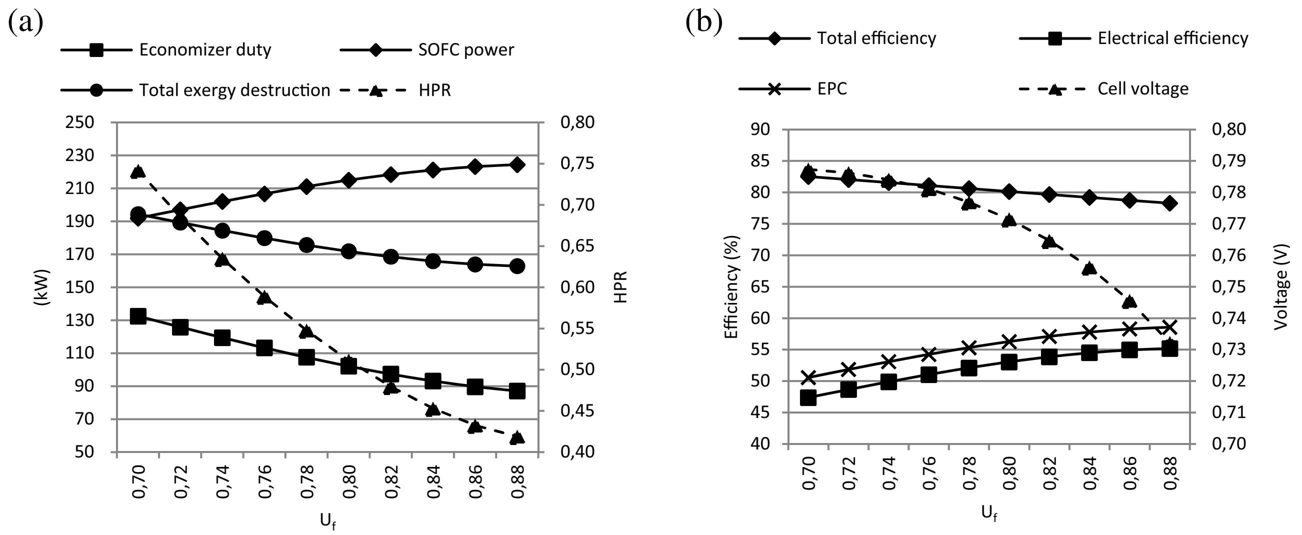

Fig. 2. Effect of fuel utilization factor on characteristics of SOFC/CHP system; (a) system powers and HPR; (b) efficiencies, exergetic performance coefficient and cell voltage.

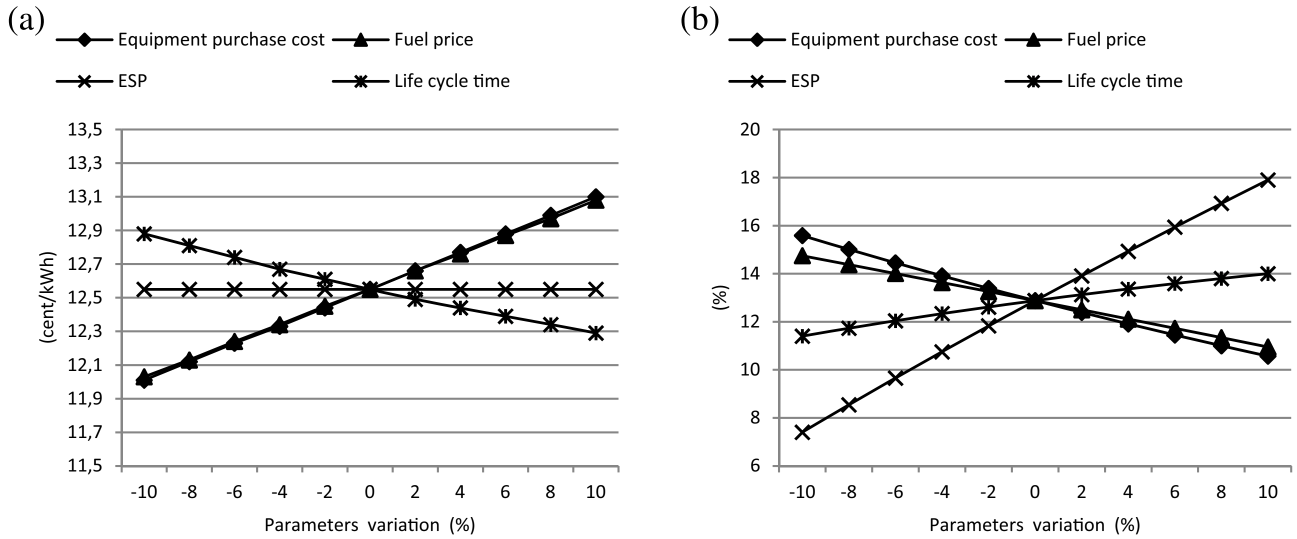

Fig. 3. Sensitivity analysis of economic characteristics of SOFC/CHP system; (a) electricity production cost; (b) IRR.

Table 6. Exergy destructions and exergetic efficiency results of SOFC/CHP system modelling.

Equipment	Exergy destructions (kW)	Exergetic efficiency (%)
Recuperator	66.4	84.13
Economizer	26.27	89.23
After burner	22.64	94.74
Exhaust exergy	21.02	0.00
SOFC	15.95	98.26
Mixer	7.21	98.81
Air blower	2.86	83.81
Pre-reformer	2.15	99.64
Total	164.8	–

in SOFC fuel consumption leads to a shortage of SOFC fuel in the afterburner and a decline in the afterburner and economizer outlets temperature.

These results also suggest an optimum utilization value for U_f, when $U_f = 0.84$, the maximum overall performance is achievable.

We also conducted a limited investigation on the effects of equipment purchase cost, fuel price, ESP and life cycle time over the following economical output characteristics:

- Total production cost as the main contributor in ESP.
- *IRR* as the main motivator for investors.

In this respect, we assumed 10% margin variation for the initial input values for equipment purchase cost, fuel price, ESP and life cycles time. Figure 3 shows the results. According to the ESP is the most influential factor in economic considerations. We can also prioritize the effect of equipment purchase cost, fuel price and life cycle time.

Any other combination of the mentioned scenarios could be investigated in further studies.

5 Conclusion

The proposed exergy based thermo-economic modelling confirms the benefits of using of SOFC technology in CHP applications, as it provides:

1. High electrical and total efficiencies (electrical efficiency of 54.77%, and total efficiency of 78.97%).
2. An environmentally-friendly cycle with low CO_2 emission compared with conventional combined power cycle fed by natural gas (19.17% reduction in CO_2 emission).
3. Appropriate *HPR* value, equal to 0.44, and high EPC, equal to 58.08.

In addition, the following scenarios have a positive effect on the widespread applications of the proposed system:

a) increasing global ESP to 122.67 \$ $MW.h^{-1}$;
b) decreasing 8% in equipment purchase costs;
c) decreasing fuel prices to 0.2031 \$ $kg.methane^{-1}$.

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