Economic Analysis of Biomass Gasification-Solid Oxide Fuel Cell-Gas Turbine Hybrid Cycle

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Abstract- In this study, an economic analysis of a hybrid system, a pressurized solid oxide fuel cell-gas turbine (SOFC-GT) with a capacity of 1.7 MW, which includes several sub-units, is conducted. Using the formulation, a cost-oriented economic survey including the equipment and the system costs is also analyzed based on a sensitivity analysis. In compared with the previous studies, the presented model consists of some distinctions and the following considerations: First, considering the field equipment, the formulations is updated; Second, considering the variable cost, a range of variations for parameters' prices is selected; Third, the objective function in non-linear mathematical optimization format is prioritized. The economic performances for the average price of energy in three different locations (Europe, US and Iran) during the cycle life time, is evaluated in these regions. The results indicate that based on current energy prices and economic conditions, Europe is the most economically justifiable by having an internal rate of return (IRR) and a payback period equal to 15.5% and the 6.7 years respectively. It has also been compared with the results of the previous economic studies.

Keywords Solid oxide fuel cell, Gas turbine, Biomass gasification, Economic modeling, Optimization

1. Introduction

Authors Due to the growing global energy consumption, high prices of energy, decreasing fossil fuel resources, and increasing local and global environmental concerns, finding an appropriate way for efficient power generation with low emissions has become a matter of issue [1-4]. Thus for some industries, it is preferable to supply their need for electricity by implementing internal power plant instead of supplying from public grid [5-7].

Combined SOFC-GT systems have attracted increasing interest around the world and are being extensively investigated by researchers [8-10]. This system is applicable for small scale plants by coupling with micro gas turbines (MGTs) for distributed generation. Modeling and optimizing the hybrid SOFC-micro gas turbine system is a subject of interest [11]. Economic considerations should also be taken into account while analyzing a power generation plant. A thermo-economic method is a proper approach for analyzing the system from both thermodynamic and economic points of view [12].

A multi-objective optimization was performed by Shirazi et al. [1] on IR-SOFC-GT system and it indicated 6.14 years for payback time in the total cost of 3.28 million US$ year^{-1} and exergy efficiency of 65.6%. Also, Sanaye and Katebi [11] investigated 4E analysis and multi-objective optimization of a micro GT and SOFC as a CHP power system. The selected design point of their model demonstrated that the payback period was about 6.3 years, where total system exergy efficiency was 60.7% and electrical energy cost was 0.057 US$ $kW^{-1}h^{-1}$.

A thermo-economic design optimization was done by Morandin et al. [13] on various types of hybrid systems using wood gasifier-SOFC. They evaluated several models such as combination GT or ST with the gasifier-SOFC system. In the configuration using the FB gasifier, SOFC, and GT, the efficiency was around 65%. Also, the minimum value of specific plant costs of the most cost-effective configuration was around 8000 US$ kW^{-1}. In a study performed by Kempegowda et al. [14], an economic analysis was carried out over an SOFC/GT power plant for two cases, including HRSG and HRSG-ST. The results from this study indicated that utilizing gasification systems would boost the total purchased costs by 15 to 20% in comparison with using mixed air-steam and air gasification systems. At the same time, comparing the two cases, a less specific plant cost has been obtained for the first case. The calculations of the study were performed on electricity sales prices of 0.2 to 0.7 US$ $kW^{-1}h^{-1}$ and a positive cash-flow of about 0.3 US$ $kW^{-1}h^{-1}$.

The exergy-economic study over an SOFC-GT conducted by Abuadala and Dincer [15] showed that the biomass gasification is a suitable approach to generate hydrogen for such systems. The approach of this study was the calculation of the unit energy cost of the process streams. The outputs were obtained based on the alteration of the gasifier performance temperature between 1023-1423 K and the electricity cost equal to 0.1046 US$ $kW^{-1}h^{-1}$. The alteration results analysis showed that increasing the gasifier temperature will contribute to hydrogen production and a decrease in unit hydrogen cost. A Thermo-economic analysis conducted by Brown et al. [16] proposed a model for the optimization of the combustion of the wood gasification with two power generation systems ICE-CC and GT-CC. The system performance was evaluated by air, oxygen and steam fluidized bed gasification. The model was resolved to obtain a 20 MW of power. Resolving the optimized model working in the trade-off condition resulted in the specific cost of a system using steam gasification is 2.1 €W^{-1} for GT-CC. That is less than the system which is utilizing the other two gasification models. WTEMP software developed at the University of Genoa was the principle source of a thermo-economic study over SOFC-GT conducted by Santin et al. [17]. They applied two types of liquid form fuels and developed a hybrid system of 500 kW which had taken into consideration of the two designing formats of planar SOFC and tubular SOFC. Considering IRR, the TSOFC-IR had the best condition by a level of 31.4%. The thermo-economic evaluation of the cycle which had employed the steam turbine as an extra power generator in SOFC-GT systems was the main theme of the study conducted by Arsalis [18]. The study was carried out over different capacities of the hybrid system within the range of 1.5 to 10 MW. The author believed that regarding the outputs of the modeling in the study, SOFC-GT-ST systems would bring up both economic and thermodynamic advantages compared with more common SOFC-GT, GT-ST or single SOFC systems. The considering both the economic benefits and the cycle efficiency results from the study also cited that hybrid systems with a higher power generation capacity were quite promising. On the other hand, the role of heat exchangers in relation to the SOFC, GT and ST has been defined economically and the necessity of cost calculation has been emphasized.

Meratizaman et al. [19] developed a new model for using the exhausted heat of SOFC–GT power cycle in a Heat Recovery Steam Generator (HRSG) to produce the required steam for a desalination unit. Their economic analyses have been applied based on the annualized cost method. Results showed that the combination of desalination unit and the SOFC–GT power system makes it more economic. Furthermore, they proposed a SOFC-GT cycle to provide the required energy in the household application [20]. The capacity range of presented system was 11 to 42.9 kW and the initial cost per kWh and the payback period have been calculated 0.0208 US$ and 8.35 years, respectively.

Najafi et al. [21] modeled a SOFC–GT hybrid system integrated with a multi-stage flash desalination unit. Optimization results indicated that the total cost of 3.76 million US$ $year^{-1}$ and the payback period time of the proposed cycle has been measured about 9 years. Furthermore, Rokni et al. [22] presented a small-scale integrated biomass gasification-SOFC and Stirling engine with a net electric capacity of 120 kW. Thermoeconomic analysis demonstrated that the generation of electricity price is 0.1204 US$ kWh^{-1} and hot water which was considered as a by-product, can be produced with 0.0214 US$ kWh^{-1}.

Muzzacco and Rokni [23] studied on a biogas-fueled SOFC integrated with different systems such as GT for electric power generation purpose. Their thermoeconomic analysis provided an average cost of electricity close to 6.4 and 9.4 c€ kW^{-1} for 10 MW capacity which is competitive within the electricity market. Caliandro et al. [24] have presented a SOFC–GT hybrid system, fueled with gasified woody biomass for small and medium scale applications. Achievements of this research have been shown that for pressurized gasification options lower specific costs can be reached compared to atmospheric systems.

Lee et al. [25] has performed an exergoeconomic evaluations for a 100 kW SOFC based combined cycle. The Levelized cost of electricity was calculated as 0.3354 US$ kWh^{-1}. On the other hand, the purchased equipment cost of the SOFC stack was assumed to be US$ 282.9 kW^{-1}, which is not significantly close to the real coat of fuel cell systems.

Illustrating the energy efficiency alterations versus the cost of energy production changes in SOFC-GT systems was carried out in a study conducted by Cheddie and Murray [26]. Coupling an SOFC system the energy efficiency showed an increase of 19.2% (from 30% to 49%) in a 10 MW power plant using a GT system. In that case, it enhanced its upper-level power generation to 21.6 MW. The coupling of the systems was implemented partially to minimize the complexity of the experimental implementation. The result of the proposed optimizing cycle model indicated that the cost of producing power diminished from 5.45 to 4.7 US\$ $kW^{-1}h^{-1}$. Nagel et al. [27] preformed a study about specific plant costs after designing seed low power generating systems (less than 600 kW) of biomass-integrated gasification fuel cell. The economic calculations were conducted based on districts technology of biomass gasification. The results from the study indicated that the gasification contributed to capital cost increase and consequently considerable power generation cost. The outcomes of the study pointed out that the power production costs of such systems were significantly high, which affected the specific plant costs in a way that the lowest level of the specific plant cost among the systems was 3000 € kW^{-1}.

According to Fig. 1, a small SOFC-GT power plant with capacity of 1.7 MW has been designed [28, 29] in which a portion of its necessary fuel is supplied by biomass gasification and then, a comprehensive economic analysis of the whole cycle has been performed by taking a novel strategy, in the present study. Consequently, in accordance with the international prices of fuel and electricity, the IRR of the plant and its competitiveness were studied in this regard.

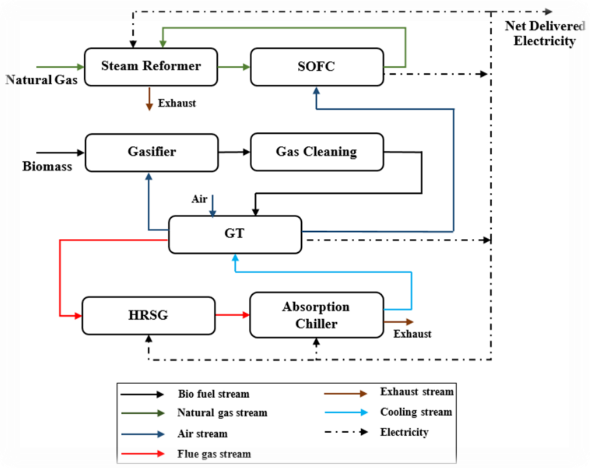

Fig. 1. Simplified process layout of an integrated gasification SOFC-GT power plant.

2. Economic Modeling

2.1. Fixed Capital Investment

The FCI costs could be divided into two groups. Some of the costs are directly associated with the type of the equipment and the way they perform at the cycle. Expenses related to the foundation, and the site preparation and the instruments are subsidiaries of this cost and are required for the preparation of each power plant. Such costs which are mainly spent on purchasing the necessary equipment and their installation were previously called the direct costs. The second group of the fixed capital investment is the cost which is not directly associated with the plant's operations but must be added to the industrial plants' fixed expenses overhead. In Section 2.1 the other major parameters affecting the direct and indirect costs have been introduced.

The purchased equipment cost is both dependent on the size and the capacity of the equipment. Such dependency is shown in Eq. (1) below:

$$EPC_{S_2} = EPC_{S_1}\left(\frac{S_2}{S_1}\right)^{ci} \qquad (1)$$

In the previous studies for the equipment's prices a different level of "ci" has been stated and it seems that an average level of 0.6 is quite fair to be considered [30]. In the present study, the designed equations employed in the calculation of the main equipment of the hybrid system have been presented according to each section in Fig. 1.

2.1.1. SOFC System Cost Functions

To calculate the SOFC system costs, different parameters which have been shown in the present study through Eqs. (2) to (4) in Table 1 [18] must be taken into account.

Table 1. Applied cost functions of SOFC, HRSG and auxiliary elements

	Cost Function	Equation number
SOFC		
C_{SOFC}	$A_{SOFC}(2.96T_{SOFC} - 1907)$	(2)
C_{aux}	$0.1\times C_{SOFC}$	(3)
C_{inv}	$10^5(\dot{W}_{SOFC}/500)^{0.7}$	(4)
HRSG		
$C_{HE(HRSG)}$	$3650\sum_i (f_{Pi}\ f_{Ti,steam}\ f_{Ti,gas} K^{0.8})_i$	(5)
f_{Pi}	$0.0971(P_i/30)+0.9029$	(6)
$f_{Ti,steam}$	$1+\exp(T_{out,steam} - 830/500)$	(7)
$f_{Ti,gas}$	$1+\exp(T_{out,gas} - 990/500)$	(8)
K_i	$(Q_i/\Delta T_{Lm,i})$	(9)
C_{piping}	$11820\sum_j (f_{Pj,steam})$	(10)
f_{Pj}	$0.0971(P_j/30)+0.9029$	(11)
C_{gas}	$685\,m_{gas}^{1.2}$	(12)
C_{HRSG}	$C_{HE(HRSG)} + C_{piping} + C_{gas}$	(13)
Auxiliary elements		
C_{HE}	$130(A_{HE}/0.093)^{0.78}$	(14)
C_{pump}	$442\ (\dot{W}_{pump})^{0.71}\times 1.41\,f_\eta$	(15)
C_{dryer}	$\exp\left\{\begin{matrix}10.158+0.1003\ [Ln(A)] \\ +\ 0.04303\ [Ln(A)]^2\end{matrix}\right\}$	(16)
C_{shs}	$760\ V^{0.22}$	(17)
$C_{HRSG\,stack}$	$0.04\,HRSG\ Cost$	(18)

The purchase cost of SOFC affects strongly on the electricity price. The SOFC purchase cost is estimated to be around 3000 € kW^{-1}, which is in fact very expensive. Also, it should be considered that the general cost of this system is categorized into SOFC stack and the auxiliary equipment costs. The auxiliary equipment costs for equipment such as a combustor mixer, by-pass valves and etc. are taken into account. As a notification, the SR cost has been estimated by Eq. (19) and the required absorbed heat to perform the chemical reaction has been obtained by SR energy balance [31].

$$C_{SR} = 0.677\, Q^{0.81} \quad (19)$$

The steam supplier is, in fact, an HRSG system which generates the LP steam required by SR. The cost calculation associated with this system has been performed by Eqs. (5) to (13) in Table 1, which has been applied for HRSG system formulation [18].

2.1.2. GT system cost functions

The gas turbine and the compressors are the major components of the GT system and the cost formulation of which have been performed by Eqs. (20) and (21). Based on these relationships, the turbine and compressor shaft work are the influential parameters on GT system cost as shown in mentioned equations. [14, 18, 32].

$$C_{GT} = \left[(-98.328\, Ln(W_{GT}) + 1318.5) \times W_{GT}\right] \quad (20)$$

$$C_{comp} = 91562\left[\frac{W_{comp}}{445}\right]^{0.67} \quad (21)$$

2.1.3. FB gasifier cost functions

FB system includes a biomass gasifier and an ash outlet has been considered within equipment purchased cost calculation based on Eqs. (22) and (23). The cost associated with the fluidized bed gasifier has been obtained based on the mentioned equations in references [33-35]. Referring to the previous studies the scale factor was considered as 0.67 and also the formula presented by [35] (for the cyclone) was applied in order to achieve the ash outlet unit cost.

$$\mathrm{C_g} = 1600 * (\mathrm{m_g})^{0.67} \quad (22)$$

$$C_{cyclone} = \exp\left\{8.9845 - 0.7892\,[Ln(S)] + 0.08487\,[Ln(S)]^2\right\} \quad (23)$$

It should be noted that, in Eq. (23) the size factor is equal to the gas flow rate in $ft^3.min^1$.

2.1.4. Gas cleaning cost functions

The Eqs. (24) and (25) have been employed to calculate the gas cleaning system purchased cost. As a technical comment, Cyclone and ceramic line separator coupled with filters used for desulfurization and removal particles from the bio-syngas [33].

$$C_{sep} = 35\, A_{mem} \quad (24)$$

$$C_{filter} = 3800\, A_{filter}^{0.52} \quad (25)$$

2.1.5. HRSG system cost functions

Achieving the HRSG system equipment purchased cost, it has been concluded that it strongly depends on heat exchangers component costs, piping component and gas conduit costs. For further context, Table 1 illustrates the HRSG cost formulation [18].

2.1.6. Auxiliary elements cost functions

The costs of other cycle's equipment which have not been mentioned in the sub-systems are estimated by the Eqs. (14) to (18) presented in Table 1. The followings include such equipment:

- Heat exchangers which have been used as fuel and air-preheaters [36].
- The pumps which enhance the water or pressured steam in the system [37, 38]. Regarding the cost function of pump calculation, the efficiency correction factor is achieved by the following Eq. (26):

$$f_\eta = 1 + \left(1 - 0.8/1 - \eta_{pump}\right) \quad (26)$$

- Using the recovered heat from the flue gas exhausted from HRSG, The batch tray biomass dryer dries up the biomass fuel, just before being sent to the unit [35].
- The solid handling system carries the dried biomass fuel to the FB system. In the present study, a screw type system performs caring the mentioned activity [35].
- Two stacks have been designated to exhaust the gasses from the HRSG-biomass fuel dryer and steam producer [38].

2.2. Other direct and indirect capital costs parameters

In the plant cycle implementation, the points mentioned in Table 2 have been considered by both the investors and the manufacturers. Therefore Eqs. (27) to (38) presented in this table, indicate the direct and indirectly estimated costs in the present study [39, 40]. It is observed that the direct cost parameters are a function of EPC. On the other hand, the indirect costs have been introduced as a function of direct costs apart from the contingency. Yet, the indirect costs constitute 15% to 30% of the FCI [30, 41].

By these means, having obtained the TVC value and calculated the factors such as fuel cost and bank installment, the annual costs of the cycle are estimated. Regarding that, the Eqs. (39) to (51) employed for the TVC estimation, including the manufacturing costs and the general expenses, are presented in Table 2.

Table 2. Applied direct and indirect cost functions

Cost Factor	Cost Function	Equation number
Fixed Capital Investment		
Direct Costs		
Equipment Purchase Costs	Section 2.1	
Installation Cost for Equipment's	$0.25(EPC) \le IC \le 0.55(EPC)$	(27)
Total Instrumentation and Control Cost	$0.06(EPC) \le ICC \le 0.3(EPC)$	(28)
Piping Cost	$0.1(EPC) \le PC \le 0.8(EPC)$	(29)
Electrical Installation	$0.1(EPC) \le EC \le 0.4(EPC)$	(30)
Building Including Services	$0.1(EPC) \le BSC \le 0.7(EPC)$	(31)
Yard Improvements	$0.1(EPC) \le YIC \le 0.2(EPC)$	(32)
Service Facilities	$0.3(EPC) \le SFC \le 0.8(EPC)$	(33)
Land	$0.04(EPC) \le L \le 0.08(EPC)$	(34)
Indirect Costs		
Engineering and Supervision	$0.05(Direct\ Costs) \le ESC \le 0.3(Direct\ Costs)$	(35)
Construction Expenses	$0.04(Direct\ Costs) \le CE \le 0.21(Direct\ Costs)$	(36)
Contractor's Fee	$0.02(Direct\ Costs) \le CF \le 0.08(Direct\ Costs)$	(37)
Contingency	$0.05(Direct\ and\ Indirect\ Costs) \le C \le 0.15(Direct\ Costs)$	(38)
Manufacturing Cost		
Direct Variable Costs		
Raw materials	$0.1(TVC) \le RM \le 0.5(TVC)$	(39)
Operating labor	$0.1(TVC) \le OPLC \le 0.2(TVC)$	(40)
Direct supervisory and clerical labor	$0.1(Operating\ labor)$	(41)
Utilities	$0.1(TVC) \le Ut \le 0.2(TVC)$	(42)
Maintenance and repairs	$0.02(FCI)$	(43)
Operating supplies	$0.15(Ma\operatorname{int}enance\ and\ repairs)$	(44)
Laboratory charges	$0.1(Operating\ labor)$	(45)
Fixed Charges		
Depreciation	$0.04(FCI)$	(46)
Local taxes	$0.01(FCI)$	(47)
Insurance	$0.004(FCI)$	(48)
General Expenses		
Administrative costs	$0.02(TVC) \le Ad\min C \le 0.06(TVC)$	(49)
Distribution and selling costs	$0.02(TVC) \le DSC \le 0.2(TVC)$	(50)
Research and development costs	$0.05(TVC)$	(51)
Financing	$0.01(TCI)$	(52)

By these means, having obtained the TVC value and calculated the factors such as fuel cost and bank installment, the annual costs of the cycle are estimated. Regarding that, the Eqs. (39) to (51) employed for the TVC estimation, including the manufacturing costs and the general expenses, are presented in Table 2.

2.3. IRR and NPV estimation

The net cash flow is calculated based on the annual incomes and expenses of the power plant. The annual expenses include the total variable cost, the fuel cost, and the annual bank's repayments. To compare these various options, it is necessary to convert all cash flows for each measure into its equivalent base. This is based on time-value-issue relate to incomes and expenditures. Regarding that, in order to calculate the annual NCF value the Eq. (53) has been applied.

$$NCF = \begin{pmatrix} Electricity\,Gross\,Payment + Steam\,Production \\ -TVC - Fuel\,Cost - Bank\,Installment \end{pmatrix} \quad (53)$$

Considering the obtained values of NCF, NPV for the life cycle is achieved by using Eq. (54):

$$NPV = \sum_{n=1}^{m} \frac{CF_n}{(1+R)^n} - TCI \quad (54)$$

Where, m is equal to 25.

The IRR is the discount rate at the zero NPV. It should be noted that, if IRR is greater than the cut-off or the hurdle rate, the proposed cycle is acceptable.

3. Results and Discussion

3.1. Model comparison

In order to compare the model presented in this paper, the results were compared with the results from the previous similar studies. As a brief statement, the results of this comparative study are presented below:

1. As noted in reference [14], the positive cash flow in the selling price of electricity has been achieved as 0.3 US$ $kW^{-1}h^{-1}$. While in the present study, the NPV value is obtained equal 0.073 US$ $kW^{-1}h^{-1}$, 0.12 US$ $kW^{-1}h^{-1}$ for the US and Europe respectively.

2. The cost of producing the required hydrogen in regard to the production costs of SR, the steam supplier, and NG are equal to 13.77, 5.08 US$ kg^{-1} in the US and Europe respectively. Those can be compared with hydrogen production costs of the system presented in reference [15] where is 10.17 US$ kg^{-1}. That system makes use of solid oxide electrolysis cell and purification of the gas produced by biomass gasification. The distinction here is mainly due to the different technologies employed in hydrogen production in the present and the referred study. On the other hand, the results indicate, taking advantage of the SR system is more economical to supply hydrogen wherever there is a better access to NG resources.

3. Having resolved the model presented in this study, the specific plant cost value for the electricity generation will be equal to 2530 US$ kW^{-1}. This value can be acceptable in comparison with the minimum value of specific plant cost around 8000 US$ kW^{-1} obtained in reference [13]. However, in that study, the use of expense wood gasifier technologies cause the total cost to be increased. The lowest value of the specific plant costs in the biomass gasification-SOFC system cited in reference [27] is approximately equal to 3000 € kW^{-1}. Examining the different obtained values show that due to the three following reasons, both studied cycles are different.

   First: SOFC is the only electricity generation system in the referred study, whereas, in the present study, a portion of the power is generated by the GT system.

   Second: the steam production in the present study in addition to the electricity generation will contribute to an increase in plant revenues.

   Third: according to the content expressed in part 2, employing different technologies for hydrogen production in both studies will affect some specific plant costs. Yet the main reason for such a comparison in this study is that more than 74% of the EPC value including the units (such as biomass, inverter, SOFC, gas cleaning and gasification), are all presented in the referred study as well. Hence, the desirability of the specific plant costs of the present study has also been confirmed.

   Also, the specific cost in reference [16], which has examined the wood gasification with two power generating systems GT-CC and ICE-CC is at best equal to 2.1 € W^{-1}. Due to the lack of SOFC system in the referred study, the value of 2.53 US$ W^{-1} indicates that the specific plant cost in the present study is rather appropriate.

4. The Percentage of the contribution of each piece of the main equipment of the cycle to the total EPC obtained by using Table 5 shows an acceptable compliance in comparison with the values presented by the referred study [18]. As it is clear, in order to conduct the comparison, the distinction between the two studies must be taken into consideration. For instance, the steam turbine system and its associated prices of equipment, as well as the internal reforming SOFC, were employed in the referred study while different items like gasifier and absorption systems have been utilized in the present study. Another worthy point is that in the present study, PSOFC inverter cost has allocated a considerable amount of 13% out of the total EPC to itself.

5. The comparison of the IRR value and payback period between the reference [17] and the present study, must be carried out by considering the fact that the cost of the electricity generated from the SOFC is assumed to

be equal to 400 US$ kW^{-1} in the referred study. Of course, such a price is currently not capable of trading. Therefore, if we compare the Europe IRR and a payback period of 15.5% and 6.7 years as real values in the present study with the ideal values of 31.4% and 3.4 years estimated for the TSOFC-ER in the referred study, a fair result is achieved in regard to the current electricity prices and SOFC.

3.2. NPV and IRR

A parametric study has been conducted to calculate NPV and IRR alterations based on the electricity price variations in the intended location. The Electricity price intervals of 0.017 US$ $kW^{-1}h^{-1}$ to 0.138 US$ $kW^{-1}h^{-1}$ which are respectively the prices in Europe and Iran have been considered in the model. According to the Fig. 2, the diagram of NPV changes for the cycle performance lifetime has been calculated. It should be noted that the negative values of NPV indicate that working in these conditions the cycle is not economical. Thus, they are not considered as acceptable outputs.

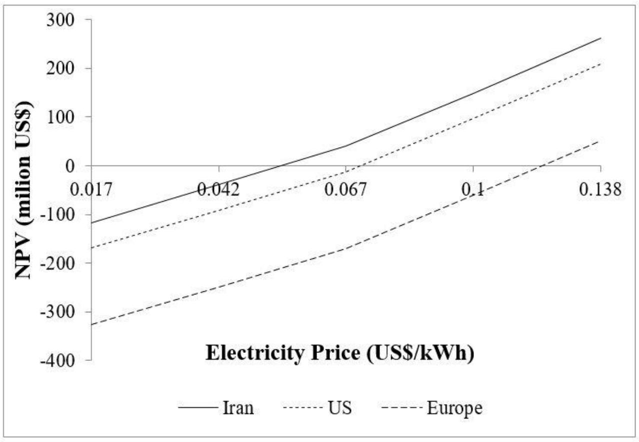

Fig. 2. Calculated NPV for considered locations based on electricity price changing

Where the IRR value is obtained at NPV=0 it is based on the discount rate which has been considered in the study. According to results shown in the Tables 3 and 4, considering the current prices of the electricity sales in Europe, the cycle has a positive value of NPV.

Table 3. NPV value changes based on different electricity and natural gas prices for considered locations

		Electricity Price (US$ kWh^{-1})				
	Natural Gas Price (US$ m^{-3})	**0.017 (CEP of Iran)**	**0.042**	**0.067 (CEP of US)**	**0.100**	**0.138 (CEP of Europe)**
Iran	**0.01**	-106,749,968	-28,566,968	49,616,032	154,597,025	267,225,985
	0.02	-111,646,027	-33,463,027	44,719,974	154,130,734	266,759,694
	0.03	-116,542,086	-38,359,086	39,823,915	149,234,675	261,863,635
	0.04	-121,438,144	-43,255,144	34,927,857	144,338,617	256,967,577
	0.05	-126,334,203	-48,151,203	30,031,798	139,442,558	252,071,518
US	**0.130**	-165,502,671	-87,319,672	-9,136,672	100,274,089	212,903,049
	0.135	-167,950,701	-89,767,701	-11,584,701	97,826,060	210,455,020
	0.138	-169,419,519	-91,236,519	-13,053,519	96,357,242	208,986,202
	0.145	-172,846,760	-94,663,760	-16,480,760	92,930,001	205,558,961
	0.150	-175,294,789	-97,111,789	-18,928,789	90,481,972	203,110,932
Europe	**0.35**	-273,215,961	-195,032,961	-116,849,961	-7,439,201	105,189,760
	0.40	-297,696,254	-219,513,254	-141,330,254	-31,919,494	80,709,467
	0.46	-327,072,606	-248,889,606	-170,706,606	-61,295,846	51,333,115
	0.50	-346,656,840	-268,473,840	-190,290,840	-80,880,080	31,748,881
	0.55	-371,137,133	-292,954,133	-214,771,133	-105,360,373	7,268,587

: Shaded numbers are acceptable results

Table 4. IRR value changes based on different electricity and natural gas prices for considered locations

		Electricity Price (US$ kWh^{-1})				
	Natural Gas Price (US$ m^{-3})	**0.017 (CEP of Iran)**	**0.042**	**0.067 (CEP of US)**	**0.100**	**0.138 (CEP of Europe)**
Iran	**0.01**	N.E.*	N.E.	15.3	26.6	39.8
	0.02	N.E.	N.E.	14.7	26.5	39.7
	0.03	N.E.	N.E.	14.1	26.0	39.1
	0.04	N.E.	N.E.	13.5	25.4	38.6
	0.05	N.E.	N.E.	12.9	24.9	38.1
US	**0.130**	N.E.	N.E.	N.E.	20.4	33.7
	0.135	N.E.	N.E.	N.E.	20.1	33.5
	0.138	N.E.	N.E.	N.E.	20.0	33.3
	0.145	N.E.	N.E.	N.E.	19.6	32.9
	0.150	N.E.	N.E.	N.E.	19.3	32.6
Europe	**0.35**	N.E.	N.E.	N.E.	N.E.	21.7
	0.40	N.E.	N.E.	N.E.	N.E.	18.9
	0.46	N.E.	N.E.	N.E.	N.E.	15.5
	0.50	N.E.	N.E.	N.E.	N.E.	13.1
	0.55	N.E.	N.E.	N.E.	N.E.	10.0

(*): Not Economical

While at the same time a negative value of NPV will be achieved for the cases of Iran and the US. In this regard, there are two points that should be considered: first, at the moment, the electricity prices in several countries around the world are higher than 0.2 US$ $kW^{-1}h^{-1}$ and second, there's the inevitable increase in energy consumption and hence the electricity prices in the coming years [42, 43]. Therefore, the economic prospective cycle presented here will bring up an appropriate economic desirability. So its application for industries that comply with the consumption rate of the proposed hybrid system is justifiable.

As previously noted, according to the results shown in Fig. 2 and Tables 3 and 4, in terms of economic conditions, the system in Europe provides better outcomes rather than Iran and the US. Also, because of the lower fuel price in Iran, in the case of increasing the electricity sales price, the growth of IRR and NPV values will be more effective than the other cases in comparison. On the other hand, by increasing the electricity sales price with the amount of 0.06 US$ $kW^{-1}h^{-1}$ in the US, the proposed system will acquire a positive NPV. Also in Table 5, the payback period of the system is shown for different electricity prices for three considered location. As illustrated in Fig. 3, the payback time period and B.E.P. for Europe electricity price characteristics, is estimated in 6.7 years.

Based on sensitivity analysis over the price of NG and consequently NPV and IRR, some new considerations about economic analysis point of view occur. Considering quantitative results shown in Tables 3 and 4 which is related to the price of NG at individual previous mentioned locations, increasing fuel price up to 0.55 $ m^{-3} based on current electricity price, seem still economical in Europe. Positive NPV and IRR equal to 10.0% are approval values to cover these results. This kind of findings can be considered as an advantage to develop the mentioned hybrid cycle more widely.

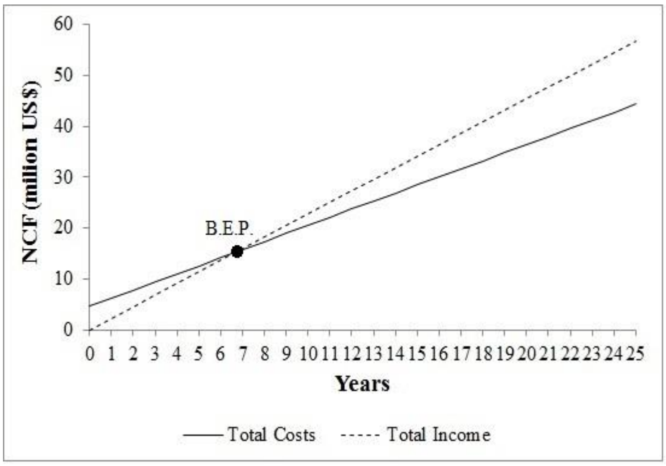

Fig. 3. Payback period time for Europe with current energy carrier prices

Table 5. Payback period of proposed power plant with different electricity prices

	Iran	US	Europe
Electricity Price (US$ kWh^{-1})	B.E.P. (years)	B.E.P. (years)	B.E.P. (years)
0.017 (CEP of Iran)	N.E.*	N.E.	N.E.
0.042	18.0	N.E.	N.E.
0.067 (CEP of US)	7.2	12.3	N.E.
0.100	4.0	4.9	N.E.
0.138 (CEP of Europe)	2.9	3.3	6.7

(*): Not Economical

3.3. Cost reduction strategy

HRSG and the absorption system elimination are considered as a cost reduction strategy. Tables 6 and 7 show the resolved model of the cycle, which has been designed within different scenarios named without absorption (S2) and without HRSG (S3). The resolved model compares the scenarios` performance with the main cycle (S1). Two viewpoints are involved in examining S2 and S3 scenarios: first, the economic prospect and second, the energy efficiency perspective because of the low rate of NPV and IRR changes for the previously mentioned sub-systems.

It is inferred that the economic confirmation is based on SOFC-GT, but since the energy (exergy) efficiency is involved, such systems are capable of being verified technologically. According to the comments stated here, the approach presented by this study (i.e. not performing the exergy cost trade-off simultaneously) has been justified. According to exergy optimization done by authors in the previous studies, accredited sensitivity analysis in the economic study is because of the presence of a cost objective function in this study [44]. The reason for not significantly achieving different values of IRR and NPV even by eliminating these two systems is that despite the reduction of the initial investment, the loss of saving (resulting from reduced NG fuel consumption with regard to the removal of absorption system) will be 100,915 m^3 $year^{-1}$.

The decrease in revenue due to steam sales in regard to the HRSG system removal (respective values of 9545 and 1618 ton $year^{-1}$ HP and LP steam) will contribute to the lack of significant changes of IRR and NPV. However, improving the overall efficiency of the cycle by employing these two systems can be omitted where there are restrictions on investment.

Table 6. Effect of HRSG and absorption chiller elimination on NPV of the proposed cycle

	Iran			US			Europe		
Electricity Price (US$ kWh^{-1})	**NPV (US$) S1**	**NPV (US$) S2**	**NPV (US$) S3**	**NPV (US$) S1**	**NPV (US$) S2**	**NPV (US$) S3**	**NPV (US$) S1**	**NPV (US$) S2**	**NPV (US$) S3**
0.017 (CEP of Iran)	-116,542,086	-108,916,093	-150,351,892	-169,419,519	-164,082,282	-203,043,363	-327,072,606	-328,559,255	-360,142,010
0.042	-38,359,086	-30,733,093	-72,168,892	-91,236,519	-85,899,282	-124,860,363	-248,889,606	-250,376,255	-281,959,010
0.067 (CEP of US)	39,823,915	47,449,908	6,014,108	-13,053,519	-7,716,282	-46,677,363	-170,706,606	-172,193,255	-203,776,010
0.100	149,234,675	156,747,468	109,215,669	96,357,242	101,581,279	56,524,191	-61,295,846	-62,895,695	-100,574,450
0.138 (CEP of Europe)	261,863,635	269,489,628	228,053,829	208,986,202	214,323,439	175,362,358	51,333,115	49,846,465	18,263,711

. Shaded numbers are acceptable results

Table 7. Effect of HRSG and absorption chiller elimination on IRR of the proposed cycle

	Iran			US			Europe		
Electricity Price (US$/kWh)	**IRR (%) S1**	**IRR (%) S2**	**IRR (%) S3**	**IRR (%) S1**	**IRR (%) S2**	**IRR (%) S3**	**IRR (%) S1**	**IRR (%) S2**	**IRR (%) S3**
0.017 (CEP of Iran)	N.E.*	N.E.	N.E.	N.E.	N.E.	N.E.	N.E.	N.E.	N.E.
0.042	N.E.	N.E.	N.E.	N.E.	N.E.	N.E.	N.E.	N.E.	N.E.
0.067 (CEP of US)	14.1	14.5	9.0	N.E.	N.E.	N.E.	N.E.	N.E.	N.E.
0.100	26.0	27.0	22.8	20.0	20.5	16.1	N.E.	N.E.	N.E.
0.138 (CEP of Europe)	39.1	40.5	37.2	33.3	34.2	30.1	15.5	14.8	10.8

(*): Not Economical

4. Conclusion

The Implementation of the economic model for a small scale plant cycle SOFC-GT coupled with the sub-systems such as biomass gasification and gas cleaning, HRSG, absorption cycle showed that in many parts of the Europe where the cost of electrical energy is high, the use of this system is now affordable.

The results of resolving the model for Europe, shows a positive value of 0.12 US$ kW^{-1}h^{-1}, with the current price of electricity in Europe, the IRR value is equal to 15.5% with 6.7 years payback period. The model outputs also indicate that for the case studies of the US and Iran increasing the electricity sales prices from the current price of 0.067 US$ kW^{-1}h^{-1} to about 0.073 US$ kW^{-1}h^{-1} in the US and 0.017 US$ kW^{-1}h^{-1} to 0.055 US$ kW^{-1}h^{-1} in Iran, will make the cycle utilizing more economically justified.

The results of the model for regions which have better access to fuel recourses and consequently lower fuel prices showed growth in IRR and NPV values in the case of an increase in electricity sales prices. So, the increase in the rate of IRR and NPV in the cases of the US and Iran are higher particularly if compared with Europe. According to what is expected, regarding the EPC values, PSOFC system in comparison with the other cycle equipment, has allocated more significant share to itself, in a way that it includes more than 55% of the total costs of the system. This has had a direct impact on TCI and TVC. Efforts made by the manufacturers to reduce the costs of SOFC will result in the fixed and current cost reduction and hence contribute to the development of the system. The calculated specific plant cost is currently 2.53 US$ W^{-1} which could be reduced if the mentioned costs are minimized.

Finally, although the elimination of the HRSG and absorption sub-systems improves initial investment conditions, in the case of a developing approach, the saving reduction of the fuel consumption by using absorption caused by the overall increased efficiency and reduced revenues from sales of steam exhausted from HRSG, will make their utilization affordable. This result has faced to a little challenge within the values of IRR, NPV; that has been achieved in most of the studied cases in this research.

5. Index

A	Surface Area, m^2
B.E.P.	Break-Even Point
C	Cost
CEP	Current Electricity Price, US$ kW^{-1}h^{-1}
CF	Cash Flow, US$
ci	Cost Index
EPC	Equipment Purchased Cost, US$
f	Factor
FCI	Fixed Capital Investment, US$
IRR	Internal Rate of Return
K	LMTD correction factor
LHV	Lower Heating Value, kJ kg^{-1}
LMTD	Log Mean Temperature Difference
NCF	Net Cash Flow, US$
NPV	Net Profit Value, US$
Q	Heat transfer rate, kW
R	Discount rate
S_1	Equipment size 1
S_2	Equipment size 2
SPC	Specific Plant Cost
TCI	Total Capital Investment, US$
TVC	Total Variable Cost, US$

Acronyms

Bio	Biomass
CC	Combined Cycle
CHP	Combined Heat and Power

ER	External Reforming
FB	Fluidized Bed
GT	Gas Turbine
HE	Heat Exchanger
HP	High Pressure
HRSG	Heat Recovery Steam Generator
ICE-CC	Internal Combustion Engine Combined Cycle
IR	Internal Reforming
LP	Low Pressure
NG	Natural Gas
PSOFC	Pressurized Solid Oxide Fuel Cell
SOFC	Solid Oxide Fuel Cell
SR	Steam Reformer
ST	Steam Turbine

Subscripts

aux	Auxiliary equipment
comp	Compressor
cyclone	Cyclone
dryer	Fuel Dryer
filter	Filter
g	Gasifier
gas	Gas side
GT	Gas turbine
HRSG	HRSG
i	Counter
inv	Inverter
j	counter
Lm	Log Mean
mem	Membrane
i	out
P	Pressure
piping	Piping
pump	Pump
sep	Separator
shs	Solid handling system
SOFC	SOFC
SR	Steam Reformer
stack	Stack
steam	Steam side
T	Temperature

Greek letters

η	Efficiency

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