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Energy price analysis of a biomass gasification-solid oxide fuel cell-gas turbine power plant

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Abstract

In this study, the effect of energy price on the development of a biomass gasification-solid oxide fuel cell-gas turbine hybrid power plant has been considered. Although these hybrid systems have been studied based on sustainable approaches, economic aspects, specifically conventional energy prices which are the principal bottleneck for the development of these new power generators have attracted little research attention. In the present study a novel energy system has been considered, a comprehensive economic model has been implemented for the proposed system, and finally the effect of energy price on the main economic factors has been investigated. The economic effects of varying energy prices in three different locations (European Union, US and Iran) were evaluated during the cycle life time of the proposed system. Estimation of the Internal Rate of Return (IRR) based on current energy prices and economic conditions for the three locations indicated that the European Union is the most economically justifiable with an IRR value of 18.15% and a payback period value of 5.8 years. In addition, the economic viability of these modern systems will be further enhanced by a slight increase of electricity prices in the US; and with reasonable changes in electricity prices it might produce the best economic gains in Iran.

1. Introduction

Solid Oxide Fuel Cell-Gas Turbine (SOFC-GT) systems have higher overall efficiency compared with non-hybrid fuel cell systems. Based on sustainable development approaches, biomass gasification has been raised as an effective alternative strategy for supplying fuel to power plants. Consequently, its application in SOFC-GT systems has been considered in multiple studies. Researchers have been investigating novel systems in various configurations with regards to biomass gasification integrated with SOFC-GT [1-4].

Biomass gasification combined with a SOFC-GT

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system has been investigated and considered in two configurations in recent research [5-8]. The majority of research publications consider the use of syngas in a SOFC or a GT configuration [5-8]. In order to increase the total efficiency (Thermal and Electrical) of hybrid systems most studies design the cycle in the form of Combined Heat and Power (CHP). The electricity production in steam turbines as a cogeneration power generator has been correlated to the power capacity and also oriented to achieve higher efficiency [9-12].
The GT technology is utilized in various countries as a cost effective method of power generation, therefore many studies and analyses have been carried out on their economic aspects and efficiency improvement. Currently, the cost of power generation by SOFC is considerably higher than GT. Over recent years there has been a great deal of effort to decrease the SOFC stack production cost to less than 200 US\$ kW^{-1} [13-17].
Some respected studies on these kinds of hybrid systems from a economic study view point have been summarized in Table 1.
In the present study, a low SOFC-GT power plant has been designed. A portion of its necessary fuel is supplied by biomass gasification. Then a comprehensive economic analysis of the whole cycle has been performed by taking a novel approach. Lastly, in accordance with the international prices of fuel and electricity, the IRR of the plant and its competitiveness have been studied.

2. System configuration

A hybrid power generating system including a SOFC-GT, as shown in Fig. 1, was presented for whole system simulation, energy losses reduction and implementing a novel design. The proposed power plant consists of multiple sections and was designed based on 1700 kW net electricity generation.
The different sections of the power plant are listed as follows: Fluidized bed gasifier, Gas cleaning unit, External reforming SOFC, GT system, Heat Recovery Steam Generator (HRSG), and Absorption system and heat exchangers. The Steam Reformer (SR) unit has been applied to generate the hydrogen required for the SOFC from natural gas. The necessary fuel for the SR combustor is supplied by the anode outlet. The needed steam is also produced in SR steam producer by utilizing heat from SR exhausted hot gases. The gasification process of biomass fuel (wood chips) has been carried out within the fluidized bed (FB) gasifier. The solid form impurities which exist in the biomass gasification process will be separated from the gases by a C, SiO_2 separator. The exhausted gas from the FB, which has multiple impurities, are not normally useable in the gas turbine and therefore could not be

Table 1. Cost factor and total efficiency of principal related studies

Hybrid Cycle Elements	Cost factor	Total Efficiency	Reference
Biomass Gasifier–SOFC–GT	8000 US\$ kW^{-1}	EnEf: 65%	[18]
SOFC–GT	0.057 US\$ $kW^{-1}h^{-1}$	ExEf: 60.7%	[19]
SOFC–GT	0.06 US\$ kWh^{-1}	ExEf: 65.6%	[20]
Biomass Gasifier–SOFC–GT	15,000-17,000 US\$ kW^{-1}	N/A	[21]
Biomass Gasifier–SOFC–GT	0.1 US\$ $kW^{-1}h^{-1}$	N/A	[5]
SOFC–GT	1670 US\$ kW^{-1}	EnEf: 67.5%	[22]
Biomass Gasifier–GT–ST	3000 € kW^{-1}	EnEf: 43.0%	[7]
SOFC–GT	0.125 US\$ $kW^{-1}h^{-1}$	EnEf: 64.5%	[23]
SOFC–GT–ST	1000 US\$ kW^{-1}	EnEf: 68.4%	[9]
SOFC–GT	0.054 US\$ $kW^{-1}h^{-1}$	EnEf: 49.0%	[24]
SOFC–GT	0.045 US\$ $kW^{-1}h^{-1}$	EnEf: 48.5%	[25]
Biomass Gasifier–SOFC	3000 € kW^{-1}	EnEf: 75.5%	[26]

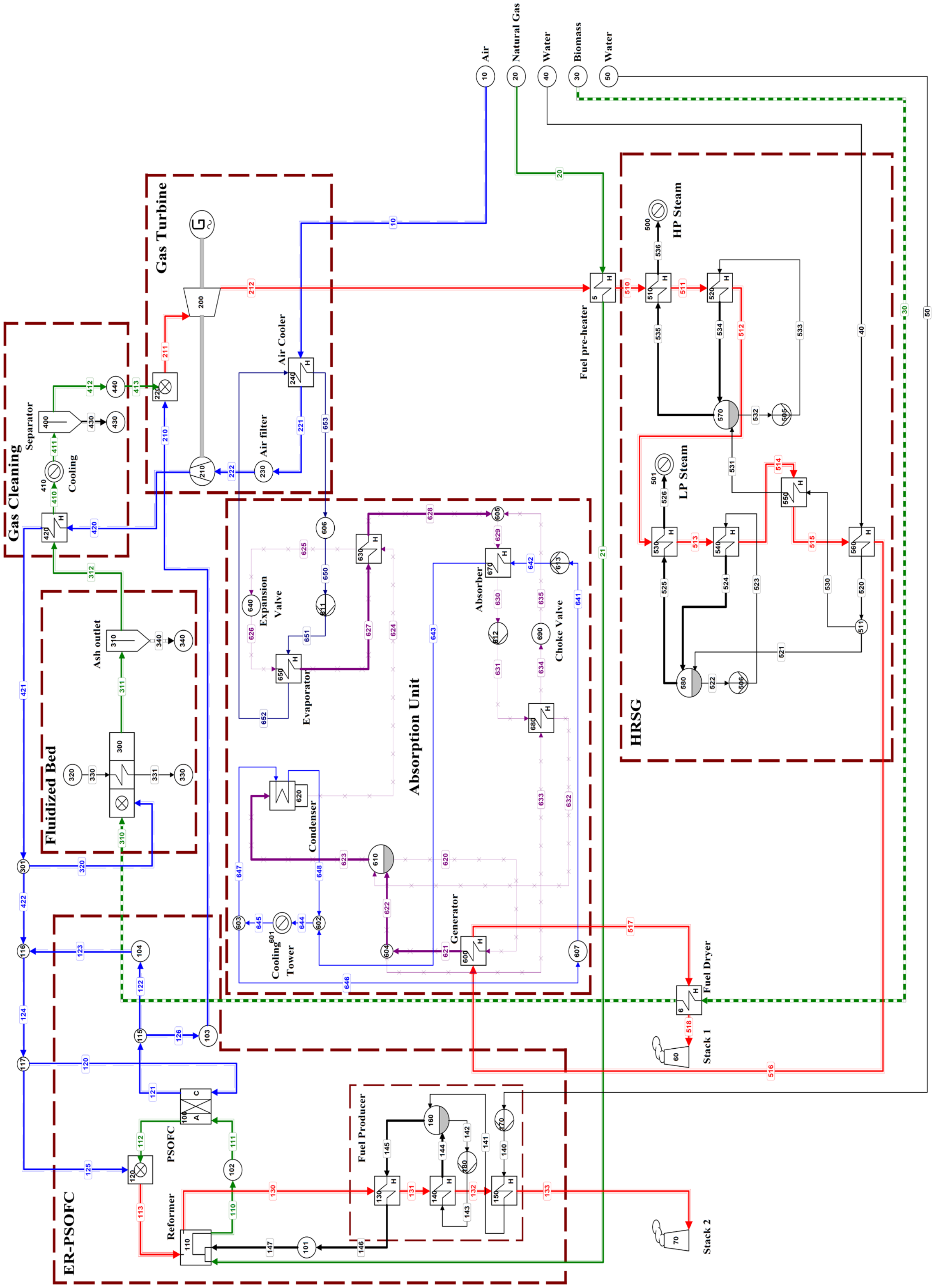

Fig. 1. Schematic of PSOFC-GT hybrid system

applied directly in the GT combustion chamber.

The exhausted GT flue gas is consumed in the HRSG unit after crossing the natural gas (NG) pre-heater. The HRSG has been designed in a dual pressure mode and produces low pressure (LP) and high pressure (HP) steam. The remarkable results from the previous studies have been applied to optimize the efficiency and enhance the steam generation capacity [27, 28].

A portion of the heat from the HRSG stack exhaust gases exchange heat in the biomass fuel dryer and then supply the required heat of the absorption system. Assumptions and input data for cycle modeling, results from the cycle simulation in the form of mass and energy balance by Cycle-Tempo software [29] have been depicted in Tables 2 and 3.

3. Economic model approach

Generally, the main objectives of implementating an economic model for the mentioned comprehensive cycle can be categorized as follows:

1. Calculation of purchase equipment costs using related equations for these types of power plants.

2. From a systematic point of view, both direct and indirect costs have been assessed and calculated. For instance, costs such as working capital, general and startup expenses, and manufacturing cost were considered. In previous studies, some of these costs factors have not been considered for SOFC-GT systems. Therefore, the reliability of the obtained results has been determined in comparison with the results of previous studies.

3. Since the general use of this cycle is the energy generation, and energy carriers' prices are a function of the location; it is assumed that the cycle is working under the present condition of fuel and electricity

Table 2. Assumptions and input data's in the model analysis

Parameter	Value (unit)	Parameter	Value (unit)
SOFC		**Gas cleaning system**	
Fuel utilization factor	0.85	Bio syn-gas outlet temperature	573.15 K
Efficiency of DC/AC conversion	0.96	**Fuel and Air inlets**	
Cell operating temperature	1073.15 K	Biomass inlet temperature	288.15 K
Stack area	700 m2	Natural gas inlet temperature	288.15 K
Cell resistance	7.5×10-5 ohm	Air inlet temperature	293.15 K
Anode & Cathode inlet temperature	1023.15 K	Biomass inlet pressure	1.013 bar
Temperature change maintained across the fuel cell	373.15 K	Natural gas inlet pressure	1.18 bar
Operating pressure	3 bar	Air inlet pressure	1.013bar
GT		**Steam reformer**	
GT and Compressor mechanical efficiency	0.99	Chemical equilibrium temperature	1073.15 K
GT isentropic efficiency	0.86	Chemical equilibrium pressure	1 bar
Compressor isentropic efficiency	0.87	Ash outlet & Separator	
Compressor pressure ratio	3.1	Syn-gas pressure drop	0.1 bar
Fluidized bed gasifier		**HRSG**	
Reaction pressure	4 bar	LP steam temperature	543.15 K
Reaction temperature	773.15 K	LP steam pressure	15 bar
Chemical equilibrium temperature	773.15 K	HP steam temperature	743.15 K
Gasifier outlet gas pressure	4 bar	HP steam pressure	50 bar
Fuel dryer		**Absorption**	
Biomass outlet temperature	373.15 K	Inlet air temperature reduction	5 K

Table 3. Main results of system simulation

Parameter (unit)	Value	Parameter (unit)	Value
Biomass consumption (kg/hr)	261.47	SOFC cell operating voltage (V)	0.7208
Natural gas consumption (kg/hr)	244.29	SOFC total over-potential (V)	0.35
SOFC electricity production (kW)	1457	SOFC stack current density (A/m^2)	3008.05
Generator electricity production (kW)	244	SOFC cathode recycle ratio	0.85
Turbine inlet temperature (K)	1269.12	LP steam production (ton/day)	4.43
Fluidized bed outlet temperature (K)	1779.49	HP steam production (ton/day)	26.97
Fluidized bed outlet flow rate (kg/s)	0.193	Gasifier cold gas efficiency (%)	70
Compressor inlet air flow rate (kg/s)	2.00	Electrical energy efficiency (%)	46.50
SOFC cathode inlet flow rate (kg/s)	9.83	Total energy efficiency (%)	82.70
SOFC anode inlet flow rate (kg/s)	0.26		

prices in the US, the European Union and Iran. The analysis of the results will provide a proper insight into the appropriateness of the present power plant and an economic prospective.

The economic feasibility of the comprehensive cycle has been carried out by estimating indicators such as Net Present Value (NPV), IRR, and payback period time. Also, discussions about indicated results and a comparison between statuses of different locations have been done.

4. Total capital investment (TCI)

Prior to the utilization of the power plant there are multiple expenses that must be specified to purchase and implement the machinery and equipment. The required capital to prepare and initiate the planning and manufacturing of the facilities is called fixed capital cost. Similarly, the required capital utilized in the units is called working capital. The sum of the fixed cost and the working costs is commonly expressed as the total capital investment. Fig. 2 presents the methodology by which the total capital investment has been calculated [30-32].

4.1. SOFC System Cost Study

Different parameters should be considered to calculate the SOFC system costs.. The most important parameters have been presented in the equations (1) to (3) [8].

$$C_{SOFC} = \mathrm{A}_{\mathrm{SOFC}}(2.96\mathrm{T}_{\mathrm{SOFC}} - 1907) \tag{1}$$

$$C_{aux} = 0.1 \times \mathrm{C}_{\mathrm{SOFC}} \tag{2}$$

$$C_{inv} = 10^5 \left(\dot{W}_{SOFC}/500\right)^{0.7} \tag{3}$$

It should be noted that the general costs of this system are divided into SOFC stack and auxiliary equipment (combustor mixer, by-pass valves, etc.) costs. The steam reformer (SR) cost has been estimated by equation (4), where Q is the required absorbed heat for the chemical reaction [23].

$$C_{SR} = 0.677\, Q^{0.81} \tag{4}$$

The steam producer is, in fact, a HRSG system which generates the LP steam required by SR. The cost calculation associated with this system has been performed by equations (5) to (13) [8].

$$C_{HE(HRSG)} = 3650 \sum_i (f_{Pi}\, f_{Ti,steam}\, f_{Ti,gas}\, K^{0.8})_i \tag{5}$$

$$f_{Pi} = 0.0971(P_i / 30) + 0.9029 \tag{6}$$

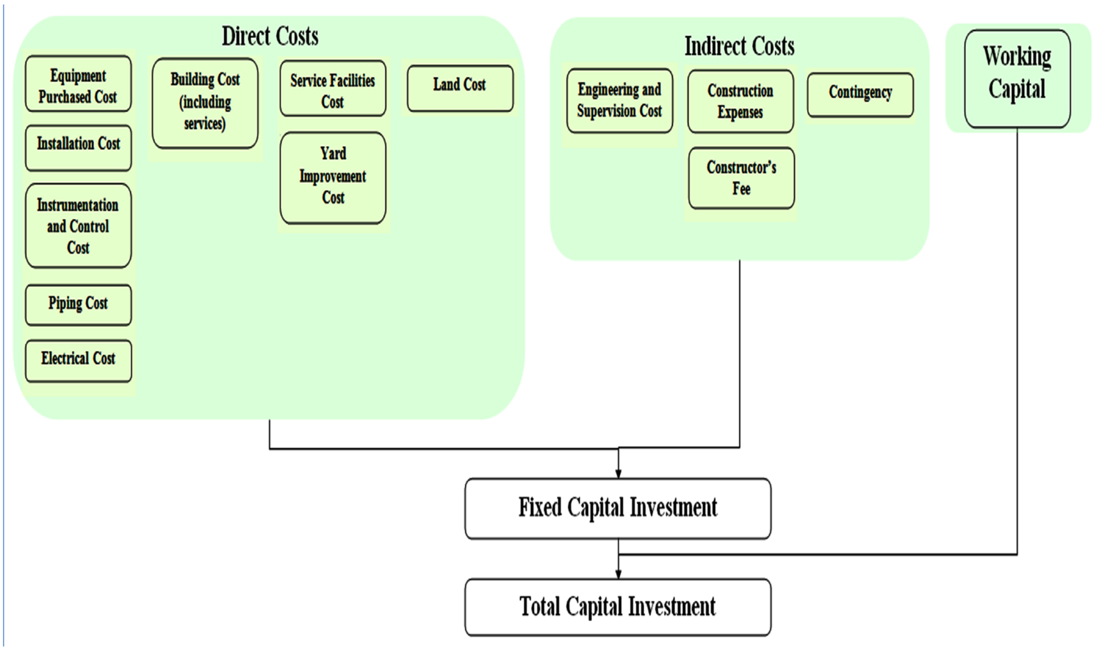

Fig. 2. The methodology of total capital investment calculation.

$$f_{Ti,steam} = 1 + \exp(T_{out,steam} - 830/500) \tag{7}$$

$$f_{Ti,gas} = 1 + \exp(T_{out,gas} - 990/500) \tag{8}$$

$$K_i = (Q_i / \Delta T_{Lm,i}) \tag{9}$$

$$C_{piping} = 11820 \sum_j (f_{Pj,steam}) \tag{10}$$

$$f_{Pj} = 0.0971(P_j / 30) + 0.9029 \tag{11}$$

$$C_{gas} = 685 m_{gas}^{1.2} \tag{12}$$

$$C_{HRSG} = C_{HE(HRSG)} + C_{piping} + C_{gas} \tag{13}$$

5. Total variable cost (TVC)

The variable costs have been examined on an annual basis in the present study. The best source of information for estimating the variable costs is to make use of data from similar projects. Because most of the companies record their financial data, the empirical relationships can be obtained for various factors. However, to obtain these factors, factors such as inflation and geographical locations must be taken into account. Based on the mentioned terminations available in section 4, and by applying General Algebraic Modeling System (GAMS) software a model was developed to find the optimal point of TVC. Each of the manufacturing costs and general expenses are divided into subsets as shown in Fig. 3.
In this model, the EPC values were calculated using the previously mentioned equations for all major equipment, and the TCI value was calculated by using equation, Numbers (1) to (13), and their contributed constraints. Additionally, the objective function is given in the form of an empirical relationship to find the TVC optimal value. In the other words, the annual costs of the cycle will be estimated by having the TVC value and calculating other factors such as fuel cost and bank installment.

6. Assumptions

In order to develop the presented model, several major assumptions have been considered as follows:

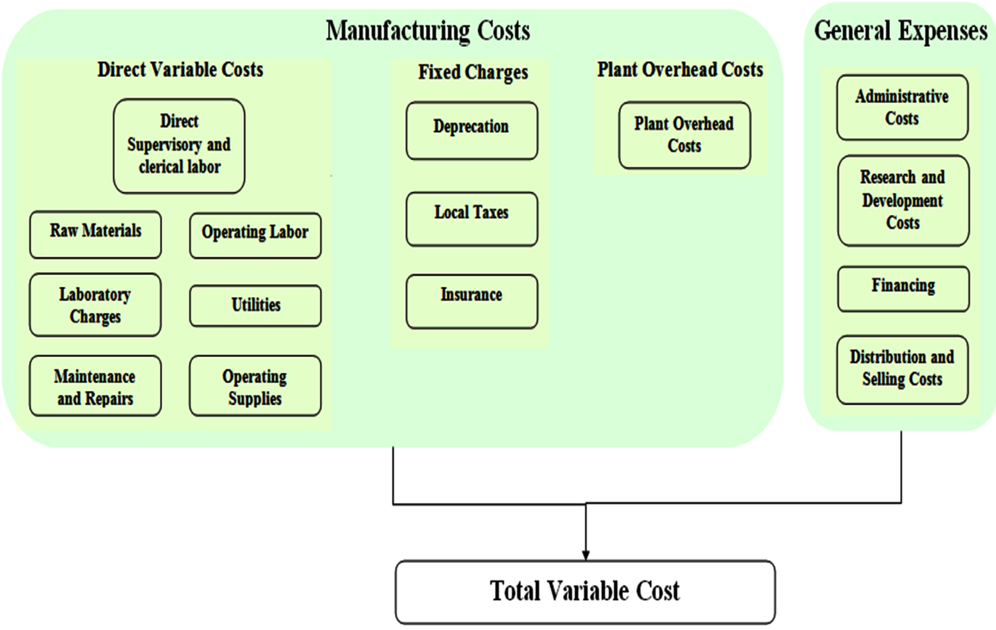

Fig. 3. The methodology of total variable cost calculation.

• The financial analysis of the hybrid power plant was estimated based on the bank's criterion. The debt and equity ratio was assumed to be 70:30 of the total capital investment.

• An interest rate of 12% for the bank installment repayment has been considered.

• The system's life cycle has been assumed to be 25 years.

• According to available data for the electricity price of industrial units in Iran, 0.017 US$ $kW^{-1}h^{-1}$ has been set. Due to the significant differences between electricity prices in most European countries and the US, the electricity price was designated based on two distinctive US and European standards. The average industrial prices were 0.136 US$ $kW^{-1}h^{-1}$ and 0.0682 US$ $kW^{-1}h^{-1}$ in Europe and the US, respectively [33, 34]. The HP and LP steam sale prices based on their international prices were assumed as 20 and 13 US$ ton^{-1}, respectively [35].

• Natural gas prices for industrial sectors in the Europe, US and Iran were assumed to be 0.40 US$ m^{-3}, 0.167 US$ m^{-3} and 0.03 US$ m^{-3}, respectively. Also, the biomass fuel price was set at 20 US$ ton^{-1} [33, 34, 36].

• Woodchips are the biomass fuel which was used in the hybrid system calculations; and fuel characteristics were obtained by referring to one of the previous studies [8].

7. Results and discussions

7.1. TCI and TVC results

The EPC estimation values of the hybrid system (discussed in section 2) are shown in Table 4. According to this table, the SOFC purchase cost are significantly higher in comparison with the other parts. The main underlying reason for this high price is the use of expensive materials in making SOFC stacks. Several attempts have been made to reduce the cost of manufacturing SOFC systems and targets have been set to achieve lower costs approximately less than the half of the current values [37]. The DC/AC inverter, HRSG and GT are ranked as the most expensive equipment of the cycle, respectively. Innovative

Table 4. Equipment purchased costs for the presented SOFC-GT hybrid system

Equipment	Cost (US$)
SOFC	888,667
GT & Compressor	239,686
Inverter	208,975
HRSG	96,608
Gasifier	66,649
Steam producer	59,016
Other equipment	46,597
Total EPC	1,606,198

technologies to fabricate a more cost effective inverter have also taken place in [38].

The obtained values of system parts, according to Figure 2, are necessary to estimate the TCI presented in Table 5. It should be mentioned that the unit cost based on total capital investment was estimated at 2719 US$ kW^{-1}. According to Table 1, this value is comparable with other respected studies. Significantly, the greater proportion of the direct costs versus indirect costs emphasizes the principal role of fixed capital investment parameters. Among the parameters affecting the direct costs, EPC is capable of having higher values.

Results of the variable and startup costs have been displayed in Table 5.

The points that should be considered about the mentioned terms in Table 5, are as follows:

1. The Plant operation has been considered as 365 days a year and 24 hours a day. Thus, costs related to a system shut down while performing maintenance has not been taken into account.

2. The insignificant costs, such as patents, royalties' costs, and building depreciation rate, have also been excluded by the total variable cost calculations.

7.2. Effect of Energy Price on Economic Factors

A parametric study has been conducted to calculate NPV and IRR alterations based on electricity price variations in the intended locations. Figs. 4, 5 and 6

Table 5. Optimum TCI & TVC results for proposed hybrid system

Cost Factor	Cost (US$)	Cost Factor	Cost (US$)
Fixed Capital Investment	3,880,700	Direct Variable Costs	202,640
Direct Costs	3,298,600	Raw materials	34,939
Equipment Purchase Costs	1,606,198	Operating labor	36,259
Installation Cost for Equipment's	402,270	Direct supervisory and clerical labor	3,626
Total Instrumentation and Control Cost	96,545	Utilities	34,939
Piping Cost	160,910	Maintenance and repairs	77,615
Electrical Installation	160,910	Operating supplies	11,643
Building Including Services	160,910	Laboratory charges	3,626
Yard Improvements	160,910	**Fixed Charges**	54,709
Service Facilities	482,720	Depreciation	32,182
Land	64,364	Local taxes	16,091
Indirect Costs	582,110	Insurance	6,437
Engineering and Supervision	190,160	**General Expenses**	74,564
Construction Expenses	131,940	Administrative costs	6,988
Contractor's Fee	65,973	Distribution and selling costs	6,988
Contingency	194,040	Research and development costs	17,470
Working Capital	431,190	Financing	43,120
Total Capital Investment	4,311,900	**Total Variable Cost**	349,390
Manufacturing Cost	274,820	**Startup Cost**	310,460

present the diagram of NPV changes contributed to the cycle performance lifetime.

The results shown in Figs. 4, 5, 6 and Table 6, illustrate that the cycle has a positive value of NPV for current electricity prices in Europe. While at the same time, negative values of NPV will be achieved in the cases of the US and Iran. In this regard, there are two points that should be considered: first, current electricity prices in several countries around the world are higher than 0.2 US$ $kW^{-1}h^{-1}$; and second, the inevitable increase in energy consumption and hence the electricity prices in the coming years [33, 34]. Therefore, the economic prospective of the presented cycle will bring up an appropriate economic desirability. So, its application for industries that comply with the consumption rate of this hybrid power plant is justifiable.

As previously noted, according to the results shown in Figures 4, 5, 6 and Table 6, in terms of economic conditions the system in Europe provides better outcomes than the systems in the US and Iran. On the other hand, by increasing the electricity sales prices by the amount of 0.03 US$ $kW^{-1}h^{-1}$ in the US, the proposed cycle will acquire a positive NPV.

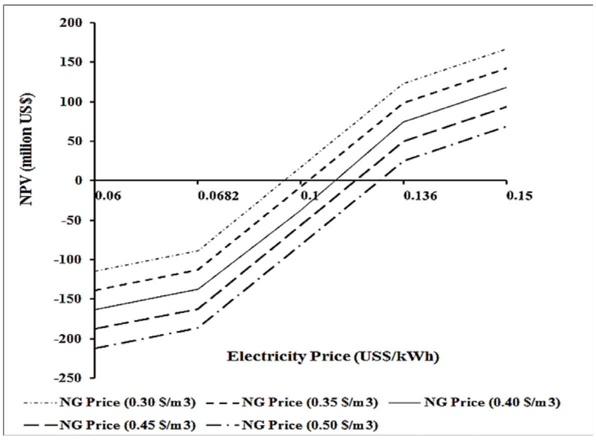

Fig. 4. NPV changes in Europe for various natural gas prices.

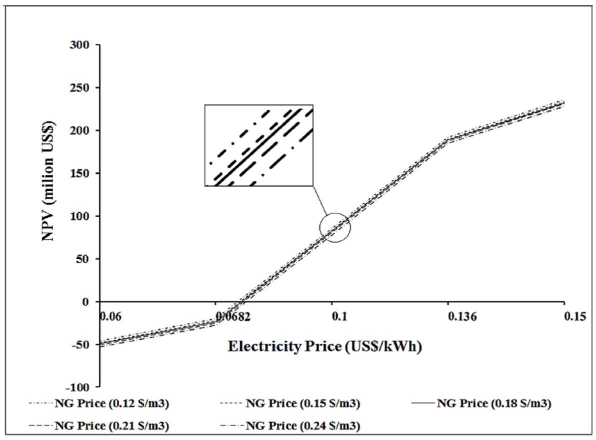

Fig. 5. NPV changes in US for various natural gas prices.

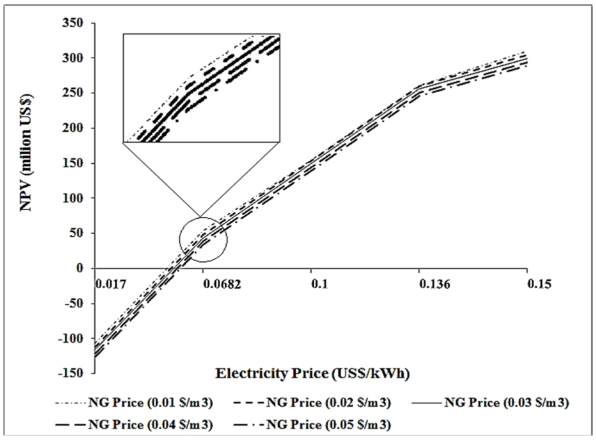

Fig. 6. NPV changes in Iran for various natural gas prices.

Also in Table 7, the payback period of the system is shown based on different electricity prices for the various considered locations. According to Figure 7, the payback time period and Break Even point (B.E.P.) for the current European electricity price is estimated at 5.8 years.

In addition, based on Figure 6 and Table 7, since the current energy price in Iran is significantly cheaper than EU and US averages, the increase slope of NPV and IRR due to increased electricity price will be steeper. However, after a subsidy reform plan in 2010, energy price has risen with a slight slope in Iran. So, by implementing reasonable changes in electricity price, Iran will become an appropriate location for the proposed SOFC-GT hybrid power plant.

Based on sensitivity analysis on NG price and consequently obtaining the values of NPV and IRR, some new considerations from an economic analysis view point have occurred. Considering the quantitative results shown in Figures 4, 5, 6 and Table 6, by increasing fuel gas price up to 0.50 \$ m^{-3} based on current electricity price, the mentioned cycle will remain economical in Europe. Positive NPV and IRR equal to 12.32% are approval values to cover these results. These kinds of findings can be investigated as

Table 6. IRR percentage in US and Europe with variable natural gas prices

		Electricity Price (US$/kWh)				
	Natural Gas Price (US$/m^3)	0.017 (Iran's EP)	0.0682 (US's EP)	0.100	0.136 (Europe's EP)	150
Iran	0.01	N.E.*	15.69	27.01	39.51	44.35
	0.02	N.E.	15.10	26.47	38.96	43.81
	0.03	N.E.	14.52	25.92	38.43	43.27
	0.04	N.E.	13.92	25.38	37.88	42.73
	0.05	N.E.	13.34	24.83	37.34	42.18
US	0.160	N.E.	N.E.	18.72	31.38	36.23
	0.165	N.E.	N.E.	18.44	31.11	35.96
	0.167	N.E.	N.E.	18.33	30.99	35.85
	0.170	N.E.	N.E.	18.16	30.84	35.69
	0.175	N.E.	N.E.	17.87	30.57	35.42
Europe	0.30	N.E.	N.E.	N.E.	23.73	28.63
	0.35	N.E.	N.E.	N.E.	20.96	25.89
	0.40	N.E.	N.E.	N.E.	18.15	23.14
	0.45	N.E.	N.E.	N.E.	15.29	20.37
	0.50	N.E.	N.E.	N.E.	12.32	18.64

(*)*: Not Economical*

advantages to develop the proposed hybrid cycle more widely.

8. Conclusion

Implementation of the economic model on a small scale SOFC-GT power plant cycle coupled with sub-systems such as biomass gasification, gas cleaning, HRSG, and absorption unit was carried out in this study. The results show that using this system is now affordable in many parts of Europe where the cost of electrical energy is high.

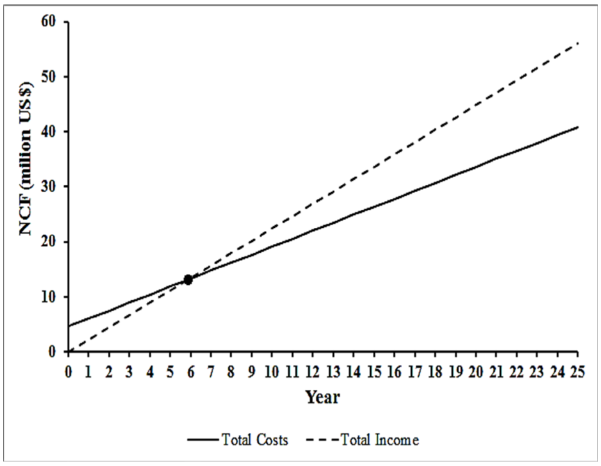

Fig. 7. Payback time period in Europe at present electricity prices.

Table 7. Amounts of B.E.P. for mentioned system in Iran, US and Europe at different electricity prices.

	Iran	US	Europe
Electricity Price (US$/kWh)	B.E.P. (years)	B.E.P. (years)	B.E.P. (years)
0.017	N.E.	N.E.	N.E.*
0.0682 (US's CEP)	7.2	N.E.	N.E.
0.100	4.0	5.7	N.E.
0.136 (Europe's CEP)	2.7	3.5	5.8
0.150	2.5	2.8	4.6

(*)*: Not Economical*

The result of implementation of the model in the EU shows a positive value of 0.12 US$ $kW^{-1}h^{-1}$. Considering the current electricity prices in Europe, the IRR value obtained is 18.15%, with a 5.8 years payback period. The model outputs also indicate that for the case of the US, an increase in the electricity sales prices from the current price of 0.0682 US$ $kW^{-1}h^{-1}$ to about 0.1 US$ $kW^{-1}h^{-1}$ will make the cycle utilization more economically justifiable. Furthermore, the current low energy prices in Iran make this system less economically justifiable, whereas any future increase in electricity prices might have more beneficial outcomes compared to other considered locations.

The results of the model for regions, such as Iran, which have better access to fuel recourses and consequently lower fuel prices, show growth in IRR and NPV values in the case of an increase in electricity sales prices. So, an increase in the rate of IRR and NPV in the US is more feasible in comparison with Europe. Considering the expected objectives, the EPC estimations show that about 55% of the cost was used up by the SOFC system in comparison with other cycle elements. Therefore, the SOFC system cost 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 further 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.

Nomenclature

B.E.P.	Break-Even Point
Bio	Biomass
C	Cost
CEP	Current Electricity Price, \$ $kW^{-1}h^{-1}$
CHP	Combined Heat and Power
comp	Compressor
EnEf	Energy Efficiency, %
EP	Electricity Price, US$
EP	Electricity Price, US$
EPC	Equipment Purchased Cost, $
ER	External Reforming
ExEf	Exergy Efficiency, %
f	Factor
FB	Fluidized Bed
gas	Gas side
GT	Gas Turbine
HE	Heat Exchanger
HP	High Pressure
HRSG	Heat Recovery Steam Generator
HRSG	HRSG
i	Counter
IRR	Internal Rate of Return
j	Counter
K	LMTD correction factor
LHV	Lower Heating Value, kJ kg^{-1}
Lm	Log Mean
LP	Low Pressure
NCF	Net Cash Flow, $
NG	Natural Gas
NPV	Net Present Value, $
out	out
P	Pressure
piping	Piping
PSOFC	Pressurized Solid Oxide Fuel Cell
Q	Heat transfer rate, kW
SOFC	Solid Oxide Fuel Cell
SR	Steam Reformer
ST	Steam Turbine
steam	steam
T	Temperature
TCI	Total Capital Investment, $
TVC	Total Variable Cost, $

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