Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2016) 24: 733 – 745

doi:10.3906/elk-1303-7

Economic assessment of a hybrid turboexpander-fuel cell gas energy extraction plant

Ahmad DARABI[1,*], **Ahmad SHARIATI**[1], **Reza GHANAEI**[1], **Ali SOLEIMANI**[1,2]
[1]Faculty of Electrical Engineering, Shahrood University of Technology, Shahrood, Iran
[2]Research Center of Marine Propulsions, Shahrood University of Technology, Iran

Received: 02.03.2013 • **Accepted/Published Online:** 02.08.2013 • **Final Version:** 23.03.2016

Abstract: In this paper, a hybrid turboexpander-fuel cell (TE-FC) is investigated for extraction of electrical energy from high pressure gas in which the fuel cells are used for preheating the gas. Combination of expanders and fuel cells will reduce the fuel consumption and greenhouse gas emission. This study reveals that there are some circumstances in which the use of fuel cells in conjunction with a turboexpander is not recommended from an economic point of view. This paper seeks the region in which utilization of fuel cells along with a turboexpander presents maximum economic profit. Using the strategy provided in this paper one can decide whether to invest in the hybrid fuel cells-turboexpander or individually planned turboexpander with a conventional gas fired preheating system. Almost all effective parameters are taken into account and this can be considered a superiority of the present paper.

Key words: Clean energy resources, gas energy extraction system, turboexpander, fuel cell

1. Introduction

The worldwide energy crisis and increasing demand for energy necessitate optimizing consumption. In this regard, many countries are compiling some programs for the future years in order to supply securely their energy requirements. On the other hand, the large amounts of greenhouse gas emissions are a global concern raising environmental concerns. Figure 1 shows the global annual carbon emissions from fossil fuels in millions of metric tons, as reported by the carbon dioxide information analysis center [1]. Considering Figure 1, one can understand the necessity for replacement of dirty fossil fuels by clean energy sources. Sometimes, partial recapturing of useless energy is a suitable way of saving energy and reducing the needs for new resources [2]. The internal energy of the fluids moving in the pipes is among such wasted energy resources. The fluids such as high pressure natural gas are available especially for transportation over long distances through long pipelines.

Supporting different customers, e.g., power plants, fertilizers, cement and metallurgical plants, and industrial districts as well as commercial and residential consumers at points along the pipeline, yields different pressure levels of delivered gas. The pressure inside the transportation pipeline has to be reduced significantly in the location of each customer. Pressure adjustment is conventionally accomplished by the regulators or throttle valves in the let down station in which the great amount of energy is usually wasted as heat. During last two decades, turboexpanders have been utilized to acquire the internal energy of the gas while reducing the pressure. The energy released during the isentropic expansion is used for rotating an expander turbine coupled with a generator. Such a system converts the gas energy to electricity while reducing the pressure of the gas

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[*] Correspondence: darabi_ahmad@hotmail.com

to a value specified properly for each customer. This system produces electrical energy without any NO_x and SO_x emissions, meeting the environmental criteria.

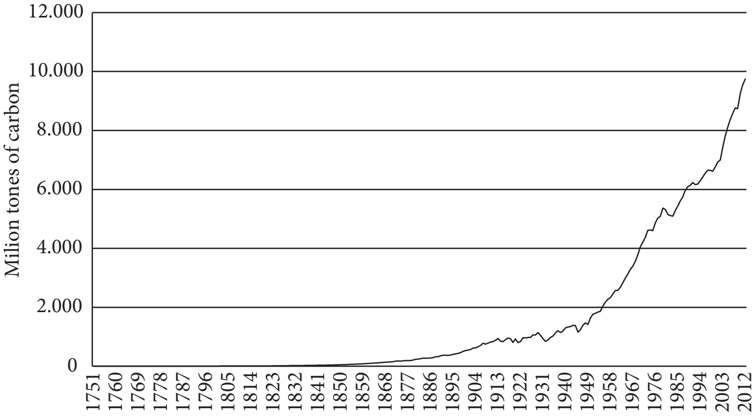

Figure 1. Global carbon dioxide emission from fossil fuel burning (www.cdiac.ornl.gov).

It is a few decades since turboexpanders were installed across the gas pipe lines and they are operating now in some countries like Italy, Russia, Germany, Denmark, the USA, and the UK. However, unavailability of the complicated technology and installation costs are the main reasons for less development and use of turboexpanders in some countries [1]. Turboexpanders were employed in steam compressors in 1978 in Denmark and then used in other applications gradually (www.cdiac.ornl.gov). A gas turboexpander is employed in Belgium's public distribution network; it was commissioned by Electrabel, Belgium's main electricity generator, the largest distributor of gas and electricity in the country. It uses a turboexpander designed to reduce natural gas pressure within 8–14 to about 1.7 bars in preparation for delivery to the final distribution network. The potential energy of the gas drives a 2.6 MW alternator [3]. Furthermore, a turboexpander is installed in a power plant at ERG's oil refinery in Priolo Gargallo, near Siracusa, Sicily in Italy. The turboexpander was manufactured at GE Energy's facilities in Belfort, France, and was shipped to the project site in late October 2004 [3]. Another turboexpander project is installed in a plant in Salizone, Italy. The turbine was designed and installed by AtlasCopco (Figure 2). The inlet and the outlet gas pressure of the turbine are 61 and 4 bars, respectively. Total flow is 60,600 Nm^3/h and the generator produces 5072 kW electric power (www.atlascopco.com).

Figure 2. Turboexpander manufactured by AtlasCopco, installed in Salizone, Italy.

An analytic method for calculation of electric power generated by the pressure of the natural gas is presented in [4]. It contains useful and practical points regarding the design of energy recovery systems based on a turboexpander. The authors of [4] explained the required number of stages, the flow rate of the gas, and the requirements of the preheater. They delivered some experimental results of a recovery system in [5]. The system was operating in Ravenna (Italy) in 1987 and produced 971 MWh electric power during two individual periods with the total length of 84 days.

The simulation results of a pressure reduction station of Czech Republic are reported in [6] in which the preheating is done by use of the heat produced by the generator, gearbox, etc. This preheating system and the influence of isentropic efficiency on the output power are studied in that paper.

In [7] a comparison between different combinations of TE-FC like a single turboexpander with a boiler, a single turboexpander with a fuel cell system, and a dual turboexpander with a fuel cell system and an expansion valve is presented. In other words, the income of the hybrid TE-FC system is studied using some cases.

A comprehensive thermodynamic analysis regarding energy and exergy calculations subject to varying operating conditions is presented in [8]. Furthermore, a simplified and novel method is used in this paper for a cost analysis to assess the amortization of the system.

Some papers like [9–12] investigate the performance of a gas turbine coupled with the fuel cell via heat exchangers. The performance of such systems depends on the operating conditions. Therefore, the authors of [9] present a parametric study to examine the effect of varying operating pressure, temperature, and current density on the performance of the system. Improving of the efficiency by increasing steam to methane ratio and pressure, and decreasing air feed rate is investigated in this paper. Although via the combination of fuel cell and power plant as the bottoming cycle better performances and higher efficiencies can be obtained, the pollution of the air as a result of burning of the gas is still a disadvantage. Therefore, simultaneous pressure reduction and electrical energy production without any pollution make the hybrid TE-FC system a distinctive and attractive alternative for energy extraction compared with other systems like the one indicated in [9].

The pressure reduction is accompanied by a temperature drop, which may cause a gas frizzing problem in the low pressure side. Therefore, preheating of the gas is essential before passing through the expansion system. It is done commonly by a gas-fired preheater while imposing fuel costs and CO_2 emissions.

The hybrid system comprising a turboexpander and fuel cells is investigated in the current paper. In this configuration both the turboexpander and the fuel cells produce electrical power while the fuel cell prepares thermal energy for preheating the inlet gas of the turboexpander too.

The ratio of turboexpander and fuel cell investment costs has a significant impact on the tolerability of the system from the economic point of view. There are many circumstances where the fuel cell utilization along with a turboexpander does not suggest any considerable profits compared with an individually operated turboexpander. A review of the literature reveals that although the hybrid TE-FC recapturing energy system is investigated in some papers, the conditions in which the profit of the TE-FC combination is more than that of an individually operated TE is not determined. Therefore, the conditions in which the use of the TE-FC combination is justified need to be studied carefully. These conditions depend on the investment cost of the TE and FC.

The present paper proposes a methodology to specify the situation where the investment on the hybrid TE-FC is reasonable regarding the target function defined properly. Using the proposed method, one can understand when the application of FCs in conjunction with a TE is profitable. In this paper, the basic concept of gas pressure energy is presented and the hybrid TE-FC system is considered from the economic point of view. The investment strategy and the simulation results are presented and finally a conclusion is given.

2. Gas energy extraction concept

The efficient transportation of natural gas from the production places to the end user locations is commonly accomplished by extensive and complex pipeline networks [3]. Natural gas is compressed at a refinery in the production place and then transported over long distances by pipelines. The pressure of the gas has to be decreased again when delivering to the customers. In general, the pressure of the gas is reduced by wasting energy devices, namely throttle valves through isenthalpic expansion. Recently, turboexpanders are suggested and employed economically in some cases for the pressure reduction of large volume gas streams extracting the electrical energy during the pressure conversion process. If the energy wasted by a conventional valve is considerable, the pressure reduction valve can be replaced by a turboexpander getting the benefit of electrical power too.

Many turboexpanders are designed to operate in the pressure within 130–200 bars. According to some publications [1] and marketing web sites [13], turboexpanders are now available from 75 kW up to 130 MW. Natural gas expansion through turboexpanders generates electric power with far greater efficiency than the conventional thermal power utilities burning gas as fuel. In addition, turboexpanders do not create greenhouse gases or significant environmental pollution [14].

For more reliability and safety of operation, the existing conventional pressure reduction valves are kept and the expansion turbines are installed in parallel with them. In this condition, the redundant standby regulator valve ensures continued safe operation in the event of turboexpander failure [15].

Most gases cool during expansion (Joule–Thompson effect) [3]. Nevertheless, temperature drop of the gas is high in the case of employing turboexpanders; therefore, preheating of the gas is required to avoid gas freezing at the outlet [6]. In some gas compositions, water or liquid hydrocarbons are produced at low temperatures that yield hydrates, blockage of the pipeline, corrosion of the blades of the turbine, and failure of the equipment. Therefore, it is essential to keep the outlet temperature above the hydrate formation range. The Hammerschmidt correlation is used to predict the hydrate formation temperature as follows [16]:

$$T = 8.9P^{0.285} \tag{1}$$

The pressure reduction by the throttle valve and turboexpander is illustrated in Appendix A. As mentioned earlier, preheating is the first stage of the pressure reduction process (points 1 and 2 of Appendix A). If the flow of gas is given by $\dot{m}$, the required power of the heat exchanger can be obtained by

$$\dot{Q} = \dot{m}\,(h_2 - h_1), \tag{2}$$

where h_1 and h_2 are the gas enthalpies before and after preheating, respectively.

After preheating, high pressure gas passes through the turbine. Pressure reduction using a turboexpander is an isentropic process that converts the released internal energy or enthalpy of the gas (points 2 and 3 of Appendix A) to electric power via a generator coupled with the shaft of the turbine. The power delivered to the turboexpander can be calculated using the equations as follows:

$$\dot{W} = \dot{m}\,(h_3 - h_2) \tag{3}$$

$$\dot{W}_{act} = \eta_{tur}\dot{W}, \tag{4}$$

where h_2 and h_3 are the enthalpies of points 2 and 3 and, $\dot{W}$ is the power released by the gas, and $\dot{W}_{act}$ is the output power of the turbine. The parameter η_{tur} is the efficiency of the turbine. Typical efficiency of the turboexpanders is within 84% to 86% [13,17,18]. In this study, the value of η_{tur} is assumed to be 0.85.

Given the temperature of the inlet gas, the temperature of the outlet gas of the turboexpander can be evaluated by [19,20]:

$$T_3 = T_2 \left(\frac{P_3}{P_2}\right)^{\left(\frac{k-1}{k}\right)}, \tag{5}$$

where P_2 and P_3 are the pressures of the inlet and outlet gas of the turboexpander, T_2 and T_3 are the temperatures of the inlet and outlet gas of the turboexpander, and k is the isentropic constant.

Gas fired heaters or multipass water-bath or oil bath heat exchangers warm the gas passing through the turboexpander [13]. The required heat can be gained from any nearby energy sources, preferably a gratis one such as energy losses in the gearboxes, generators, gas engines, fuel cells, etc. [15]. Fuel cells generate electric power, heat, and water from combination of hydrogen and oxygen with efficiency up to 85% of combined heat/electricity. Fuel cells burn the natural gas and produce more electricity per unit of fuel while releasing less carbon content pollution in comparison with combustion technology [3].

A hybrid energy extraction system as shown in Figure 3 employs a turboexpander working in parallel with fuel cells both generating electricity. Therefore, in this combined technology, the energy required for preheating the gas is prepared by the fuel cells. Additional energy is provided by the heat exchanger if necessary [3].

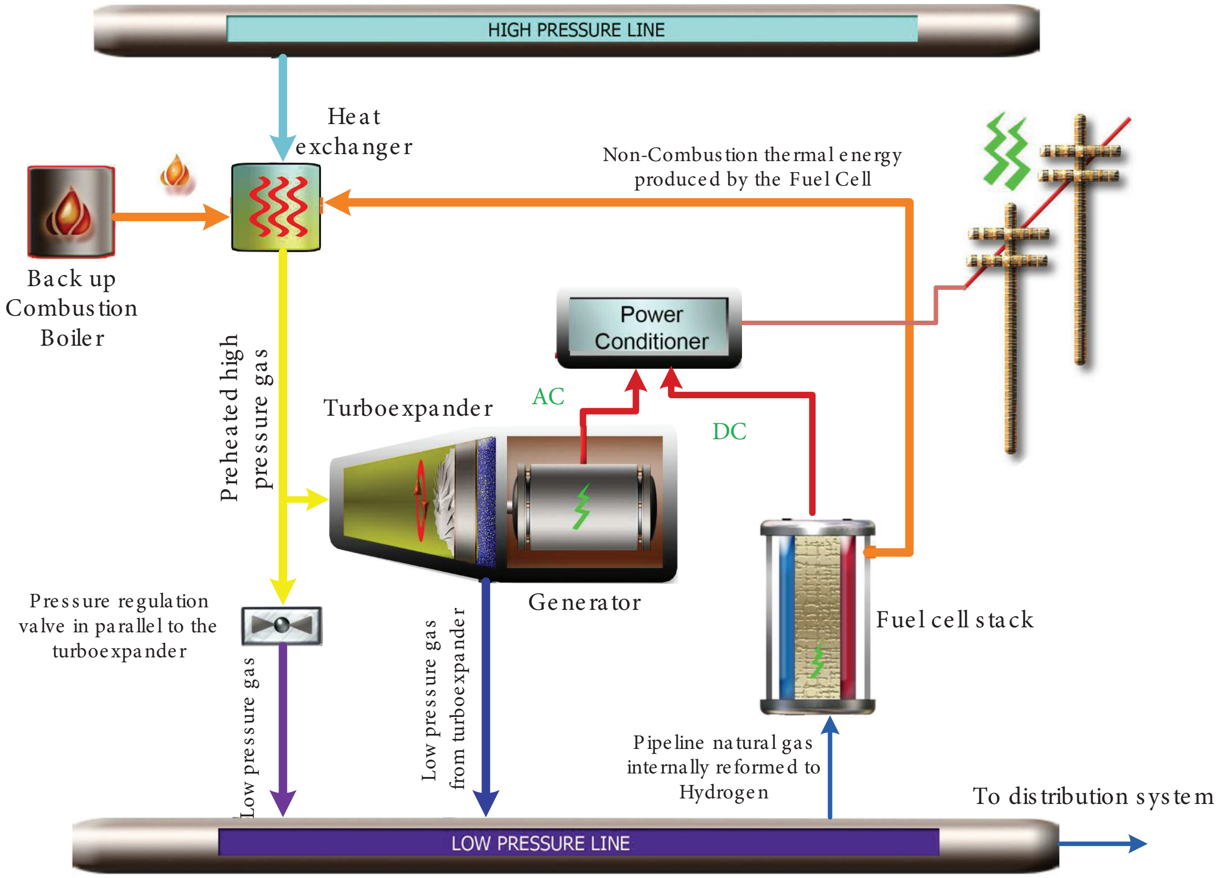

Figure 3. Hybrid turboexpander-fuel cell electric energy extraction system [15].

3. Economic assessment

For the economic assessment of the combined fuel cell-turboexpander application in gas pressure reduction stations, investment cost and annual profit comprising the fuel, maintenance, and operation costs have to be evaluated. For this purpose, in the first step the required thermal power is calculated using the temperature, pressure, and flow of the inlet gas. The volume of consuming gas is determined according to the heating value of the gas and then the energy extracted from the turboexpander is evaluated versus the pressures of the inlet and the outlet gas and the efficiency of the turbine. Subsequently, the fuel consumption and the electrical and thermal powers of the fuel cells are determined according to specifications available for the fuel cells.

3.1. Investment and annual profit

The initial investment cost of the project is the summation of the installation costs of the turboexpander $(TEInv)$, the fuel cells $(FCInv)$, and the heat exchanger $(ExcInv)$ written as

$$PR = TEInv + FCInv + ExcInv \tag{6}$$

The annual profit is the difference between the income of the electric power and the operation costs, the latter involving the fuel cost and the maintenance costs of the equipment. Therefore, the annual profit can be calculated using the equations given as

$$PMT = TERev + FCRev - ExcFuel - FCFuel - TEOM - FCOM - ExcOM \tag{7}$$

$$PMT = k1 * P_{TE} + k1 * P_{FC} - k2 * (\dot{Q}_{Tot} - \dot{Q}_{FC}) * C_{Fuel} - \frac{k1 * P_{FC}}{e_{fc-elec} * HV_{fuel}} \times \frac{C_{Fuel}}{C_{Elec}} - P_{TEMax} * OM_{TE} \tag{8}$$

$$k1 = 8760 * 3600 * C_{Elec} \tag{9}$$

$$k2 = \frac{8760 * 3600}{e_{Exc} * HV_{fuel}} \tag{10}$$

$$\dot{Q}_{FC} = \alpha * P_{FC} \tag{11}$$

The symbols used in the above equations are explained in the nomenclature. For further investigation let us define variables X, Y and Z as below:

$$X = \frac{C_{Fuel}}{C_{Elec}} \tag{12}$$

$$Y = \frac{P_{FC}}{P_{TE}} \tag{13}$$

$$Z = \frac{C_{FC}}{C_{TE}} \tag{14}$$

Applying the defined variables in Eqs. (12), (13), and (14), Eqs. (6) and (8) can be rewritten respectively as

$$PR = k15 + k11 * Y * Z - k13 * Y \tag{15}$$

$$PMT = k14 + k7 * Y + k8 * X + k9 * Y * X + k4 * Y * Z \tag{16}$$

The coefficients used in Eqs. (15) and (16) are given in Table 1. In coefficient $k4$, γ is the O/M coefficient, which indicates the operation and maintenance cost as a percent of investment cost. The transition from Eq. (8) to Eq. (16) is presented in Appendix A.

Table 1. List of variables.

$k3 = 1 - OM_{TE} * P_{TEMax} / P_{TE}$
$k4 = -P_{TE} \times \gamma \times C_{TE}$
$k5 = k3 * P_{TE}$
$k6 = -OM_{Exc} * \dot{Q}_{TotMax}$
$k7 = P_{TE} * (k1 + \alpha * OM_{Exc})$
$k8 = -C_{Elec} * k2 * \dot{Q}_{TotMax}$
$k9 = P_{TE} * (k2 * \alpha * C_{Elec} - k1/(e_{fc-elec} * HV_{fuel}))$
$k10 = P_{TEMax} * C_{TE}$
$k11 = P_{TE} * C_{TE}$
$k12 = \dot{Q}_{TotMax} * C_{Exc}$
$k13 = P_{TE} * \alpha * C_{Exc}$
$k14 = k5 + k6$
$k15 = k10 + k12$

The fuel cell is a clean energy producer with no greenhouse gases. However, the fuel cells may be considered costly; thus the necessity of economic assessment is inevitable. Two economic criteria are addressed in the next section for economic assessment.

4. Economic criteria calculation

Variation in the currency influences the economic evaluations. Particularly in some countries due to sanctions and political and economic instabilities, variation in the national currency versus international ones is substantial. For considering this matter properly, a discounting rate as an alternative of currency variation is employed for the profit evaluation. In fact, discounting rate is a parameter that indicates the profit of the same money if it were invested in other projects instead.

Internal rate of return (IRR) is the discounting rate at which the costs of the project are equal to its profits. Therefore, IRR is the real profit of the project obtained by solving the nonlinear equation of

$$-PR + PMT\left(\frac{(1+r)^n - 1}{r \times (1+r)^n}\right) = 0 \tag{17}$$

Payback period (PP) is one of the most important criteria in the economic evaluation. PP is a period in which the profit of the project covers the capital investment costs. Therefore, PP can be calculated as

$$PP = \frac{Log\left(\frac{PMT}{PMT - r \times PR}\right)}{Log(1+r)} \tag{18}$$

Installation of fuel cells with a turboexpander will be reasonable if any increment in the capacity of the fuel cells improves the economic criteria, e.g. decreases the payback period or increases the internal rate of return. It means the rates of variations of PP and IRR versus capacity increment of fuel cells are negative and positive, respectively. Obviously the reasonable boundaries of the fuel cells investment correspond to the conditions in which the variation of the aforementioned criteria with respect to capacity of the fuel cells becomes zero.

To clarify the procedure, let us consider a pressure reduction station in which the flow, temperature, and pressure of the inlet gas are as given in Table 2.

The pressure and temperature of the output gas are regulated at 250 psi and 10 °C, respectively. Using these data, the enthalpies of the input and output gas of this station are determined and given in Table 2. In order to calculate the thermal power required to preheat the gas, at first the temperature of the inlet gas of the turboexpander (as given in Table 2) is determined using Eq. (5). The enthalpy of the inlet gas of the turboexpander is then determined. Finally, using the flow of the gas and the difference between the enthalpies of the inlet and outlet gas of the exchanger, the required total thermal power as given in Table 3 is calculated by Eq. (2).

Table 2. Data of pressure reduction station.

Month	Flow (m^3/s)	Flow (kg/s)	P_1(psi)	T_1 (°C)	h_1 (kJ/kg)	P_2(psi)	T_2 (° C)	h_2 (kJ/kg)	P_3 (psi)	T_3(°C)	h_3(kJ/kg)
Jan	3.47	138.9	780	16	–76.5	780	103	145.6	250	10	–50
Feb	3.49	128.1	720	15	–75	720	94.6	129	250	10	–50
March	3.26	155.2	770	16	–75.2	770	102.2	145.4	250	10	–50
April	2.93	126.9	855	21	–70.2	855	108	161	250	10	–50
May	2.85	135.5	920	19	–80	920	115	174.5	250	10	–50
June	2.74	140.5	985	18.5	–86.6	985	119	185.5	250	10	–50
July	2.97	158.8	1030	20	–85.8	1030	126	200.2	250	10	–50
Aug	2.84	160.5	1090	21	–86.5	1090	130	209	250	10	–50
Sep	3.05	179.1	1140	23	–79.7	1140	132.3	216.1	250	10	–50
Oct	3.14	160.0	980	19	–90.5	980	118.5	181.64	250	10	–50
Nov	3.24	152.3	905	17	–89.8	905	112.7	169.7	250	10	–50
Dec	3.40	145.8	830	16	–80.8	830	107	154	250	10	–50

Table 3. Required thermal power calculation.

Month	Avg. flow (kg/s)	Δh_{1-2} (kJ/kg)	$\dot{Q}$(Mw)	$\dot{Q}$(10^{12}J)
Jan	138.9	222.1	45.4	80.0
Feb	128.1	204.0	47.4	67.8
March	155.2	220.7	53.0	88.7
April	126.9	231.2	43.6	78.6
May	135.5	254.5	39.5	92.3
June	140.5	272.1	34.2	102.4
July	158.8	286.0	30.8	121.7
Aug	160.5	295.5	26.1	127.0
Sep	179.1	295.8	34.2	141.9
Oct	160.0	272.1	29.3	112.9
Nov	152.3	259.5	34.5	102.5
Dec	145.8	234.8	38.2	88.7

Table 4 shows the monthly electrical power produced by the turboexpander. Knowing that, the investment cost and the annual profit are calculated applying Eqs. (15) and (16) and then the IRR and PP are obtained using Eqs. (17) and (18). Considering the peripheral losses, the efficiency of the heat exchanger is assumed to be 70% in this calculation. Moreover, the heating value of the gas is assumed to be 37200 kJ/m^3. Figures 4 to 7 show the PP and the IRR of the TE-FC combination studied in this paper versus capacity of the fuel cells for various values of X and Z.

According to Figures 4 and 5, for a few values of X within 0.5 to 2.5, the PP decreases and the IRR increases as the capacity of fuel cells increases.

However, as seen in Figures 6 and 7, increasing the parameter Z makes the hybrid turboexpander-fuel cells less acceptable from the economic point of view. A larger Z yields a longer PP value and a smaller IRR value.

Table 4. Output power of the turboexpander and fuel cell.

Month	Average flow (kg/s)	$\Delta h_{2\text{-}3}$ (kJ/kg)	P_{Out} (MW)	
			TE	FC
Jan	160.0	266.1	26.2	3
Feb	179.1	259	22.9	3
March	160.5	250.2	21.9	3
April	158.8	235.5	18.2	3
May	140.5	224.5	16.7	3
June	135.5	211	14.7	3
July	126.9	195.4	16.7	3
Aug	155.2	179	12.6	3
Sep	128.1	195.6	14.9	3
Oct	138.9	204	16.4	3
Nov	145.8	219.7	18.4	3
Dec	152.3	231.6	20.4	3

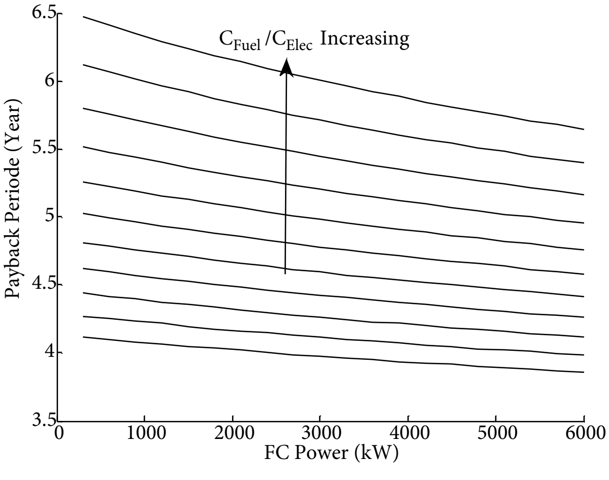

Figure 4. Payback period versus power of fuel cells for various values of X.

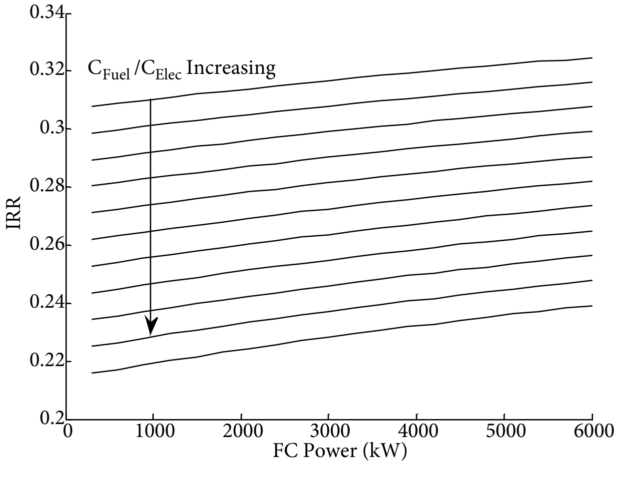

Figure 5. Internal rate of return versus power of fuel cells for various values of X.

There is a value of Z at which any increase in fuel cell capacity does not affect the economic criteria. Therefore, there is a boundary for the reasonable investment region represented here by Z*. For any larger value of Z, as the capacity of fuel cells increases the economic situation becomes worse. This means that in such condition utilizing fuel cells along with a turboexpander is not economical.

Z* corresponds to the condition in which the variation of the PP/IRR with respect to the capacity of the fuel cells is zero, i.e.

$$\frac{\partial PP}{\partial P_{FC}} = \frac{\partial\left(\frac{Log(\frac{PMT}{PMT-r\times PR})}{Log(1+r)}\right)}{\partial P_{FC}} = 0$$

$$\frac{\partial\left(Log(\frac{PMT}{PMT-r\times PR})\right)}{\partial P_{FC}} = 0$$

$$\frac{\partial PMT}{\partial P_{FC}}\times(PMT-r\times PR)-\frac{\partial(PMT-r\times PR)}{\partial P_{FC}}\times PMT=-\frac{\partial PMT}{\partial P_{FC}}\times r\times PR+\frac{\partial(r\times PR)}{\partial P_{FC}}\times PMT=0 \quad (19)$$

$$A\times(k7+k9\times X)\ +Z\times(k4\times A+D\times(k14+k8\times X))\ \ -C\times(k8\times X+k14)=0 \quad (20)$$

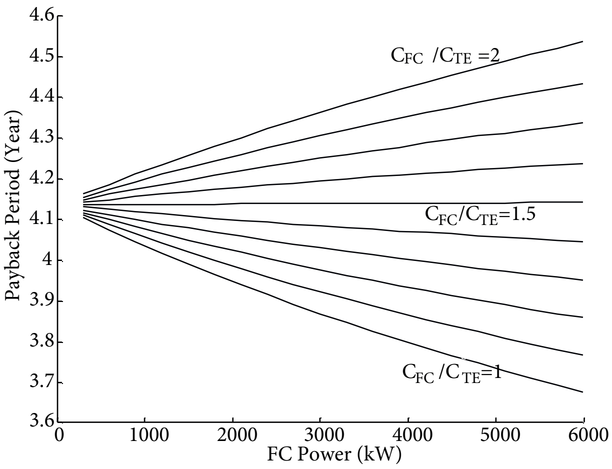

Figure 6. Payback period versus power of the fuel cells for various values of Z.

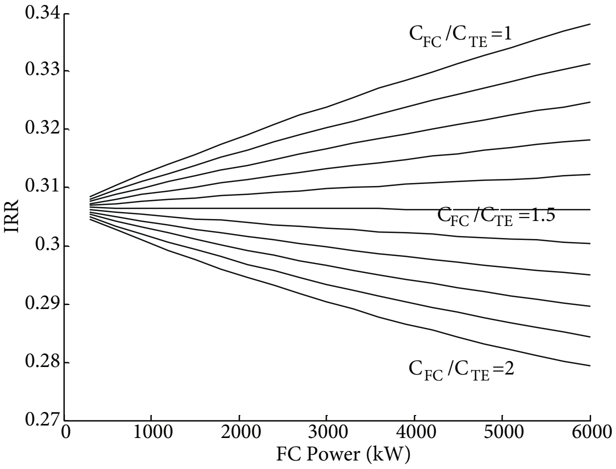

Figure 7. Internal rate of return versus power of the fuel cells for various values of Z.

Therefore, the value of Z* becomes

$$Z^* = \frac{C\times(k8\times X+k14)-A\times(k7+k9\times X)}{(k4\times A+D\times(k14+k8\times X))} \quad (21)$$

The variables of Eqs. (19) to (21) were defined earlier in Table 1. The transition from Eq. (19) to Eq. (20) is presented in Appendix A. As seen in Eq. (21) and illustrated by Figure 8, the value of Z^* depends on the value of X. This figure shows the situation where the investment in the hybrid TE-FC plant is reasonable regarding the economic point of view. Using Figure 8, one can decide whether to utilize the hybrid turboexpander-fuel cells or an individual turboexpander regarding the economic aspects such as fuel and electrical energy prices. In other words, for a given fuel to electrical energy price, the hybrid FC-TE system is reasonable if the FC to TE investment cost is lower than the critical value indicated in Figure 8.

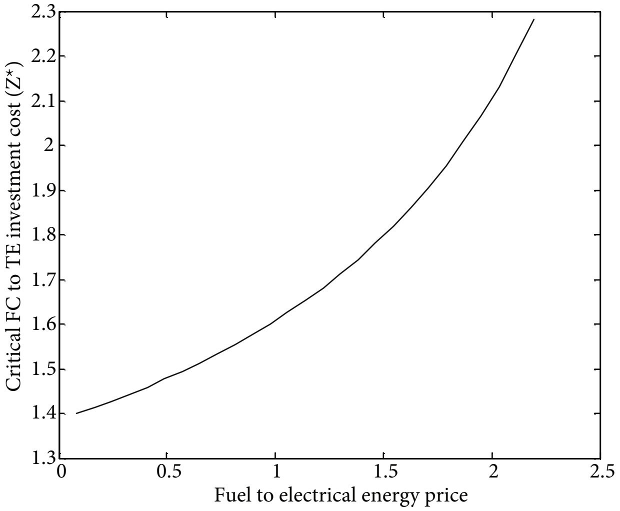

Figure 8. Critical value of Z (Z^*) versus X.

5. Conclusion

For the purpose of extracting electrical energy from gas flow, this paper presented a detailed investigation for replacing the existing pressure reduction valves by hybrid plants comprising turboexpanders and fuel cells. A procedure for economic assessment was developed and the results were given. The results indicate that from the economic point of view, utilization of fuel cells may be undeserved in some conditions. These depend on the turboexpander and fuel cell investment costs, fuel cost, and electrical energy price. Any increase in the fuel cells to turboexpander investment costs ratio makes the hybrid system less acceptable. A critical value for the fuel cells to the turboexpander investment cost ratio was obtained indicating the boundary of the profitable fuel cell application. It is shown that for a value larger than the critical value, utilization of fuel cells along with a turboexpander will not be economically acceptable. Considering the daily increasing advances in fuel cells technology, the authors think that the method proposed in this paper can be applied to evaluate the reasonability of hybrid TE-FC utilization with some confidence.

Nomenclature

T	Temperature (°F)
P	Pressure (psi)
$\dot{W}$	Power
$\dot{W}_{act}$	Output power of the turbine delivered to the generator
$\dot{m}$	Flow of gas
h	Enthalpy of gas
$\dot{Q}$	Thermal power
η_{tur}	Efficiency of the turbine
k	Isentropic constants
TE	Turboexpander
FC	Fuel cell
TEInv	Total investment cost of turboexpander
FCInv	Total investment cost of fuel cell
ExcInv	Total investment cost of exchanger
C_{FC}	Fuel cell investment cost per kW (\$/kW)
C_{TE}	Turboexpander investment cost per kW (\$/kW)
PR	Investment cost
PMT	Annual profit
TERev	Annual revenue of the turboexpander
FCRev	Annual revenue of the fuel cells
ExcFuel	Annual fuel cost of the heat exchanger
FCFuel	Annual fuel cost of the fuel cell
TEOM	Annual operation and maintenance cost of the turboexpander
FCOM	Annual operation and maintenance cost of the fuel cell
ExcOM	Annual operation and maintenance cost of the exchanger
P_{TE}	Average output power of the turboexpander
P_{FC}	Average output power of the fuel cell
$\dot{Q}_{Tot}$	Required total thermal power

$\dot{Q}_{FC}$	Thermal output power of the fuel cells	α	Thermal to electrical power ratio of the fuel cells
C_{Fuel}	Fuel cost ($\$/m^3$)		
$e_{fc-elec}$	Electrical efficiency of the fuel cells	e_{Exc}	Efficiency of the heat exchanger
HV_{fuel}	Heating value of the fuel (BTU/m^3)	γ	O/M coefficient
C_{Elec}	Electrical energy price ($/kWh)	r	Discounting rate
P_{TEMax}	Maximum output power of the turboexpander	n	Life time of the hybrid system
		PP	Payback period
$\dot{Q}_{TotMax}$	Required maximum thermal power	IRR	Internal rate of return

Acknowledgments

The authors would like to thank the Iranian National Science Foundation (INSF) for the financial support and the Research Centre of Marine Propulsions, Shahrood University of Technology, Iran, where the project was conducted.

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A. Appendix

Figure A.1 shows the gas pressure reduction by the pressure reduction valve (PRV).

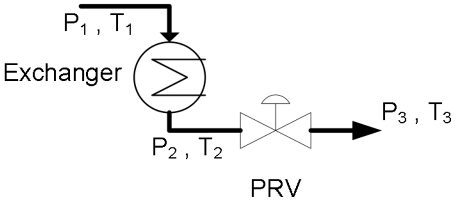

Figure A.1. Gas pressure reduction by PRV.

Figure A.2 shows the gas pressure reduction by the combination of the turboexpander and the fuel cell (TE-FC).

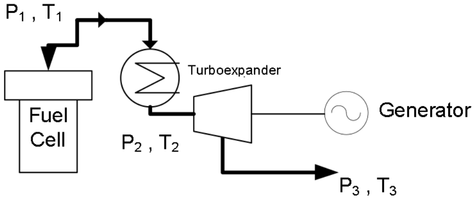

Figure A.2. Gas pressure reduction by TE-FC combination.

The annual profit of the hybrid turboexpander-fuel cell plant was expressed earlier in Eq. (8) and repeated here for convenience:

$$PMT = k1 * P_{TE} + k1 * P_{FC} - k2 * (\dot{Q}_{Tot} - \dot{Q}_{FC}) * C_{Fuel} - \frac{k1 * P_{FC}}{e_{fc-elec} * HV_{fuel}} \times \frac{C_{Fuel}}{C_{Elec}} - P_{TEMax} * OM_{TE} \\ - P_{FC} * OM_{FC} - (\dot{Q}_{TotMax} - \dot{Q}_{FC}) * OM_{Exc}$$

This equation can be summarized as Eq. (16). For this purpose, first rewrite the equation as below:

$$PMT = -\dot{Q}_{TotMax} \times OM_{Exc} + [(k1 - P_{TEMax} \times OM_{TE}) \times P_{TE}] + [k1 \times P_{FC} + P_{FC} \times \alpha \times OM_{Exc}] - \\ k2 \times \dot{Q}_{Tot} \times C_{Fuel} + k2 \times P_{FC} \times \alpha \times C_{Fuel} - P_{FC} \times \gamma \times C_{FC} - \frac{k1 * P_{FC}}{e_{fc-elec} * HV_{fuel}} \times \frac{C_{Fuel}}{C_{Elec}}$$

Considering $\dot{Q}_{FC} = \alpha * P_{FC}$ the above equation can be rewritten as the following:

$$PMT = k6 + k5 + P_{TE} \times (k1 + \alpha \times OM_{Exc}) \times \frac{P_{FC}}{P_{TE}} - C_{Elec} \times k2 \times \dot{Q}_{Tot} \times \frac{C_{Fuel}}{C_{Elec}} \\ + \left[k2 \times \alpha \times C_{Elec} - \frac{k1}{e_{fc-elec} * HV_{fuel}} \right] \times P_{TE} \times \frac{C_{Fuel}}{C_{Elec}} \times \frac{P_{FC}}{P_{TE}} - P_{TE} \times \gamma \times C_{TE} \times \frac{C_{Fuel}}{C_{Elec}} \times \frac{P_{FC}}{P_{TE}}$$

Substituting the coefficients defined in Table 1 and considering Eqs. (12)–(14), the above equation can be summarized as below:

$$PMT = k6 + k5 + k7 \times Y - k8 \times X + k9 \times Y \times X + k4 \times Y \times Z$$

This equation is presented as Eq. (16) in the paper.

In addition, Eq. (19) can be simplified as Eq. (20). For this purpose, first Eq. (19) can be written as the following using Eqs. (15) and (16):

$$(k7/P_{TE} + k9/P_{TE} \times X + k4/P_{TE} \times Z) \times (-r \times k15 - rk11 \times Y \times Z + r \times k13 \times Y) \\ + (r \times k11/P_{TE} \times Z - r \times k13/P_{TE}) \times (k14 + k7 \times Y + k8 \times X + k9 \times Y \times X + k4 \times Y \times Z) = 0$$

Multiplication of the terms can extend the above equation as:

$$
\begin{aligned}
&-k7 \times r \times k15/P_{TE} - k9 \times X \times r \times k15/P_{TE} - k4 \times Z \times r \times k15/P_{TE} - k7 \times r \times k11 \times Y \times Z/P_{TE} \\
&-k9 \times X \times r \times k11 \times Y \times Z/P_{TE} - k4 \times Z \times r \times k11 \times Y \times Z/P_{TE} + k7 \times k13 \times r \times Y/P_{TE} \\
&+k9 \times X \times k13 \times r \times Y/P_{TE} + k4 \times Z \times k13 \times r \times Y/P_{TE} + r \times k11 \times Z \times k14/P_{TE} + k7 \\
&\times Y \times r \times k11 \times Z/P_{TE} + k8 \times X \times r \times k11 \times Z/P_{TE} + k9 \times Y \times X \times r \times k11 \times Z/P_{TE} \\
&+k4 \times Y \times Z \times r \times k11 \times Z/P_{TE} - r \times k13 \times k14/P_{TE} - k7 \times Y \times r \times k13/P_{TE} - k8 \times X \times \\
&r \times k13/P_{TE} - k9 \times Y \times X \times r \times k13/P_{TE} - k4 \times Y \times Z \times r \times k13/P_{TE} = 0
\end{aligned}
$$

The above equation can be simplified as below:

$$
\begin{aligned}
&-k7 \times r \times k15/P_{TE} - k9 \times X \times r \times k15/P_{TE} - k4 \times Z \times r \times k15/P_{TE} + r \times k11 \times Z \times k14/P_{TE} \\
&+k8 \times X \times r \times k11 \times Z/P_{TE} - r \times k13 \times k14/P_{TE} - k8 \times X \times r \times k13/P_{TE} = 0
\end{aligned}
$$

Define some symbols as below:

$$A = -r \times k15/P_{TE}$$

$$B = r \times k14/P_{TE}$$

$$C = r \times k13/P_{TE}$$

$$D = r \times k11/P_{TE}$$

Finally, with substituting of A, B, C, and D, Eq. (19) can be expressed as below:

$$A \times (k7 + k9 \times X) + Z \times (k4 \times A + D \times (k14 + k8 \times X)) - C \times (k8 \times X + k14) = 0$$

This equation is presented as Eq. (20) in the paper.