

Study of fuel cell co-generation systems applied to a dairy industry

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Abstract

This paper presents a methodology for the study of a molten carbonate fuel cell co-generation system. This system is applied to a dairy industry of medium size that typically demands 2100 kW of electricity, 8500 kg/h of saturated steam ($P = 1.08$ MPa) and 2725 kW of cold water production. Depending on the associated recuperation equipment, the co-generation system permits the recovery of waste heat, which can be used for the production of steam, hot and cold water, hot and cold air. In this study, a comparison is made between two configurations of fuel cell co-generation systems (FCCS). The plant performance has been evaluated on the basis of fuel utilisation efficiency and each system component evaluated on the basis of second law efficiency. The energy analysis presented shows a fuel utilisation efficiency of about 87% and exergy analysis shows that the irreversibilities in the combustion chamber of the plant are significant. Further, the payback period estimated for the fuel cell investment between US\$ 1000 and US\$ 1500/kW is about 3 and 6 years, respectively. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Fuel cell; Co-generation; Energy analysis; Exergy analysis; Economic analysis

1. Introduction

The successive energy crises have been instigating the study of more efficient ways for the use of the available energy in fuels. In this context, new technical plants have been conceived seeking primary energy conservation. Co-generation, which is a technique of primary energy conservation, involves the generation of electricity and useful heat from a single fuel. The most important requirement in this technique is the ability to generate electricity and produce high-grade heat at low cost. Co-generation systems using fuel cells have high efficiency and lower emission of pollutants in comparison with other technologies. The high-temperature fuel cells are most suited for co-generation applications because they are able to produce high-temperature steam. In this configuration, the fuel cell is optimised to produce maximum thermal efficiency and maximum temperature of the usable heat [1].

Fuel cells are electrochemical energy conversion devices that convert fuel and oxidant electrochemically into electrical energy, water and other chemical by-products. Compared with traditional generating technologies that use combustion processes first to convert fuel to heat and mechanical energy, fuel cells convert the chemical energy of a fuel to electrical energy directly, without intermediate conversion processes.

Fuel cells, therefore, are not limited by the Carnot efficiency of thermal engines. Further, the thermal energy recovered from fuel cell units can be used in co-generation applications.

In this work, energy, exergy and economic analyses of a molten carbonate fuel cell co-generation system and applied to a dairy industry are presented. This system uses natural gas as the fuel and operates on electric parity. The system can utilise a heat recovery steam generation (to produce saturated steam) or an absorption refrigeration system (to produce cold water). The plant performance has been evaluated on the basis of fuel utilisation efficiency and each system component evaluated on the basis of second law efficiency. The energy analysis shows an electrical efficiency of 45% and a fuel utilisation efficiency of about 87%. The exergy analysis shows the exergy losses (irreversibilities) in the combustion chamber of the plant are significant. Further, the payback period estimated for the fuel cell investment between US\$ 1000 and US\$ 1500/kW is about 3 and 6 years, respectively.

2. Fuel cell system

Although, fuel cells are not heat engines, significant quantities of heat are still produced in a fuel cell power system and this must be removed. Depending upon the size of the system, the temperature of the available heat, and the requirements of the particular site, this thermal energy can

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Nomenclature

C_p	molar specific heat (kJ/kmol/K)
C_F	fuel cost (US\$/kWh)
C_{AG}	specific cold water cost (US\$/kWh)
C_{EL}	specific electricity cost (US\$/kWh)
CM	maintenance cost (US\$/kWh)
C_v	specific saturated steam cost (US\$/kWh)
E	energy (kW)
E_c	recovered heat (kW)
E_p	electricity produced in the co-generation system (kW)
E_R	electricity required by the building (kW)
ex	specific flow exergy (kJ/kmol)
Ex	exergy (kW)
f	annuity factor (per year)
GP_{EL}	annual saving for the electricity production (US\$ per year)
GP_{PF}	annual saving for the cold water production (US\$ per year)
GP_v	annual saving for the saturated steam production (US\$ per year)
h	specific enthalpy (kJ/kmol)
h_0	specific enthalpy in the ambient reference (kJ/kmol)
H	operation period (h per year)
I	equipment investment (US\$)
I_{PL}	total plant investment (US\$)
k	amortization period (year)
Los	energy losses in the co-generation system (kW)
LHV	lower heat value (kJ/kg)
N	molar flow rate (kmol/s)
N_p	molar production rate (kmol/s)
P	pressure (MPa or atm)
P_0	pressure in the ambient reference (MPa or atm)
P_{el}	buying price of electricity (US\$/kWh)
PE_{PF}	equivalent price of cold water in an electrical refrigeration system (US\$/kWh)
P_f	refrigeric power (kW)
PV_{EL}	sale tariff of the electricity surplus (US\$/kWh)
Q	heat transfer rate (kW)
R	total annual saving (US\$ per year)
R_G	universal gas constant (kJ/kmol/K)
s	specific entropy (kJ/kmol/K)
s_0	specific entropy in the ambient reference (kJ/kmol/K)
T	temperature (K)
T_0	temperature in the ambient reference (K)
W	work output rate (kW)

Greek letters

χ	mole fraction
η_F	fuel utilisation efficiency or first law efficiency
η_{II}	second law efficiency

μ^0 electrochemical potential in the ambient reference (kJ/kmol)

Subscripts

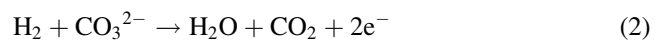
ARS	absorption refrigeration system
CH	chemical
CS	co-generation system
el	electrical
F	fuel
HRSG	heat recovery steam generator
P	process
S	supplied
TM	thermal mechanical

either be rejected, used to produce steam or hot water, or converted to electricity via a gas turbine or steam bottoming cycle or some combination thereof [2].

A molten carbonate fuel cell (MCFC) is often referred to as a second-generation fuel cell. This system uses a carbonate electrolyte (generally a mixture of lithium and potassium carbonates) and operates at 600–700 °C. The high operating temperature is needed to achieve sufficient conductivity of the electrolyte. A schematic of a molten carbonate fuel cell is shown in Fig. 1. At the cathode, oxygen reacts with carbon dioxide and electrons to form carbonate ions [3]:



The carbonate ions flow through the electrolyte matrix from cathode to anode. At the anode, the carbonate ions are consumed by oxidation of hydrogen to form steam and carbon dioxide releasing electrons to the external circuit [3].

**3. Energy requirements**

The establishment chosen for this study is a dairy industry of medium size. The typical electrical, steam and frigorific demands are 2100 kW, 8500 kg/h of saturated steam ($P = 1.08$ MPa) and 2725 kW, respectively; the last value refers to the cold water production at 1 °C, for the frigorific chamber of the factory.

4. The co-generation system

A comparison is made between two configurations. The first one (case 1) consists mainly of a molten carbonate fuel cell associated with a heat recovery steam generator, as shown in Fig. 2. The second one (case 2) consists mainly of a molten carbonate fuel cell associated with an absorption refrigeration system, as shown in Fig. 3. Both cases work

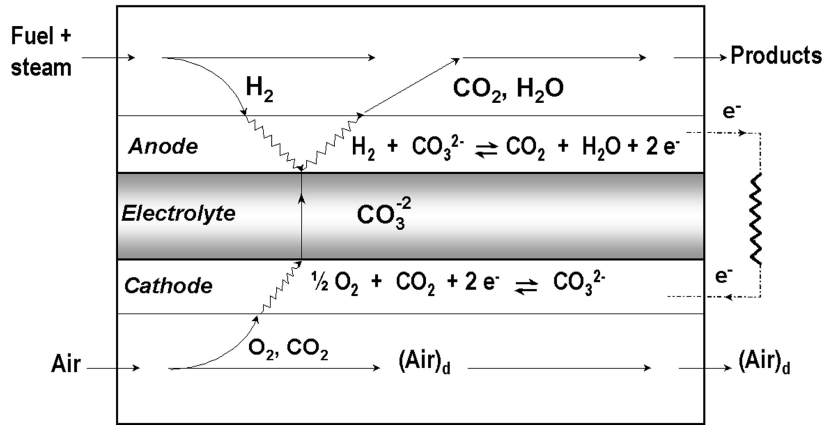


Fig. 1. Schematic of a molten carbonate fuel cell [7].

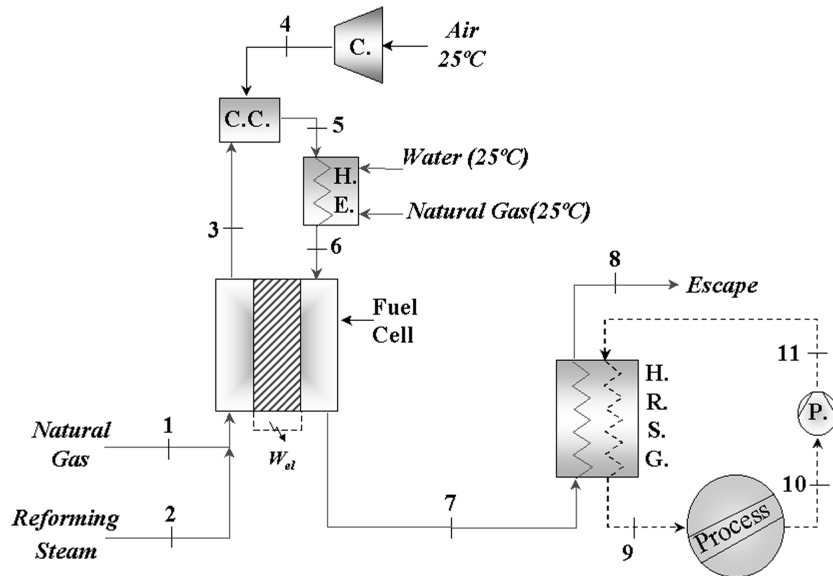


Fig. 2. Co-generation system, case 1: (C, compressor; CC, combustion chamber; HE, heat exchanger; P, pump; HRSG, heat recovery steam generator).

supplying all the electrical needs of the plant. The main parameters of system components are presented based on some existing situations [4–6]. The conditions of fuel cell components are in accordance with Dunbar et al. [7]. When necessary supplementary information was introduced for the calculation procedures.

5. Thermodynamic analysis

Energy analysis of a thermal system is based on the first law of thermodynamics which embodies the following two distinct assertions [8]:

- A system can interact with its surroundings in only two ways, namely work and heat.
- There is a property called energy whose change gives the net effect of these interactions.

The balance of each of the chemical species is [7]:

$$\sum_{out} N_j = \sum_{in} N_j + N_p \tag{3}$$

The first law, applied to each subsystem may be written as [7]

$$\sum_{in} E_i + Q = \sum_{out} E_i + W \tag{4}$$

Assuming ideal-gas behaviour, the enthalpies may be obtained from [7]:

$$E_i = \sum_j N_{ij} h_j \tag{5}$$

where

$$h_j = h_0 + \int_{T_0}^T C_{p_j} dT \tag{6}$$

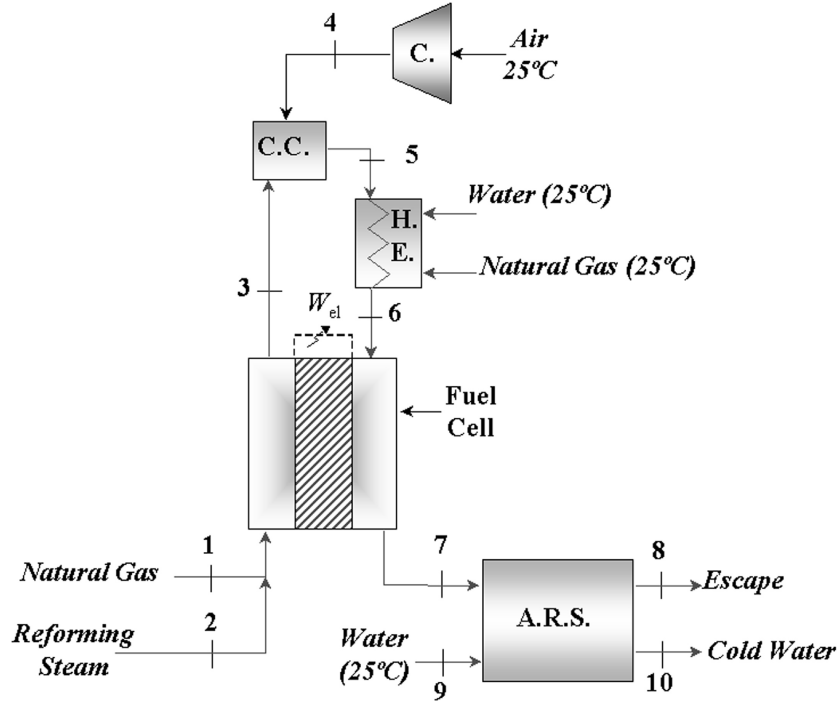


Fig. 3. Co-generation system, case 2, (C, compressor; CC, combustion chamber; HE, heat exchanger; ARS, absorption refrigeration system).

The entropy is [7]:

$$s_j = s_{j0} + \int_{T_0}^T C_{p_j} \left(\frac{dT}{T} \right) - R_G \ln \left(\frac{P_j}{P_0} \right) \quad (7)$$

Exergy analysis is based on the second law of thermodynamics according to which complete transformation of heat into work is not possible [8]. Exergy can be defined as the maximum obtainable work from a given form of energy using environmental parameters as the reference state. One of the main uses of this concept is in the exergy balance, which may be looked upon as an account of degradation of energy. In the absence of magnetic, electrical and nuclear effects, the exergy of a stream, if the changes in kinetic and potential exergies are neglected, is given by [8]:

$$ex_j = ex_{TM,j} + ex_{CH,j} \quad (8)$$

where

$$ex_{TM,j} = \int_{T_0}^T C_{p_j} \left[1 - \left(\frac{T_0}{T} \right) \right] dT + R_G T_0 \ln \left(\frac{P}{P_0} \right) \quad (9)$$

$$ex_{CH,j} = h_j(T_0) - T_0 s_j(T_0, P_0) + R_G T_0 \ln \chi_i - \mu_j^0 \quad (10)$$

Finally, the total exergy of stream i is [7]:

$$Ex_i = N_i \sum_j \chi_{ij} ex_{ij} \quad (11)$$

Exergy analysis requires that the environment be defined. The temperature and pressure of the environment were set

equal to the reference temperature and pressure (25 °C, 1 atm). The atmosphere was modelled as an ideal-gas mixture with the composition shown in Table 1 [9].

The fuel utilisation efficiency is the ratio of all the useful energy extracted from the system (electrical and process heat) to the energy of the fuel input. Thus [8],

$$\eta_F = \eta_{el} + \eta_c = \frac{W_{el} + E_c}{E_F} \quad (12)$$

The second law efficiency of co-generation systems may be defined as the ratio of the amount of exergy of products to the amount of exergy supplied. This parameter is a more accurate measure of the thermodynamic performance of the system. Thus [8]:

$$\eta_{II} = \frac{W_{el} + Ex_P}{Ex_S} \quad (13)$$

Table 1
Mole fractions and chemical exergy of the reference components in atmospheric air [9]

Component	Mole fraction ($\chi_{0,i}$)	Chemical exergy (kJ/kmol)
N ₂	0.7567	691.1
O ₂	0.2035	3946.7
H ₂ O	0.0303	8667.9
CO ₂	0.0003	20108.5
Ar	0.0092	11622.3

6. Economic analysis

The economic viability for the proposed system depends on the electricity, saturated steam, and cold-water production costs being lower than those for conventional systems. International experience shows that high electricity tariffs encourage investment in co-generation systems with capacity classes corresponding to those in this study [10].

The expressions for specific electricity cost (C_{EL}), specific steam cost (C_v) and specific cold water cost (C_{AG}) vary from system to system, and may be determined by [10]:

$$C_{EL} = \frac{(I_{PL} - I_{ARS})f}{HE_p} + \frac{C_F[E_F - E_c - (Los/2)]}{E_p} + CM_{CS} \quad (14)$$

$$C_v = \frac{I_{HRSG}f}{HE_v} + \frac{C_F}{E_v} \left[E_c + \left(\frac{Los}{2} \right) \right] + CM_{HRSG} \quad (15)$$

$$C_{AG} = \frac{I_{ARS}f}{HP_f} + \frac{C_F}{P_f} \left[E_c + \left(\frac{Los}{2} \right) \right] + CM_{ARS} \quad (16)$$

$$Los = E_F - E_p - E_c \quad (17)$$

The specific cost of steam production in a conventional boiler (C_{vc}) is [10]

$$C_{vc} = \frac{I_{CB}f}{HE_v} + \frac{C_{oil}}{\eta_B} + CM_{CB} \quad (18)$$

All costs take civil installation, electrical equipment, control system, piping and local assembling into consideration.

The annual savings due to electric power, saturated steam and cold-water production can be calculated by [10]:

$$GP_{EL} = E_R H(P_{el} - C_{EL}) + (E_p - E_R) H(PV_{EL} - C_{EL}) \quad (19)$$

$$GP_v = E_v H(C_{vc} - C_v) \quad (20)$$

$$GP_{PF} = P_f H(PE_{PF} - C_{AG}) \quad (21)$$

The total annual saving is the sum of the annual savings [10]

$$R = GP_{EL} + GP_v \quad (22)$$

or

$$R = GP_{EL} + PPF \quad (23)$$

7. Steam reforming of natural gas

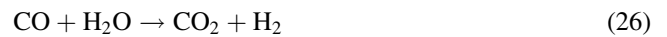
According to Gardner [11], the electrochemical oxidation of a hydrocarbon fuel is not yet a practical option. Several chemical reaction pathways, competing with electrochemical oxidation, occur more readily. Some of these lead to unwanted carbon formation and result in damage. Steam is added to a hydrocarbon fuel to prevent carbon formation. Depending on the catalytic nature of the fuel electrode, this

Table 2
Natural gas composition [10]

Component	Relative molecular mass	Vol.%	LHV (kJ/kg)
CH ₄	16.042	89.35	50143.75
C ₂ H ₆	30.068	8.03	47593.33
C ₃ H ₈	44.094	0.78	46454.55
C ₄ H ₁₀	58.120	0.07	45810.34
C ₅ H ₁₂	72.048	0.01	45445.83
CO ₂	44.009	0.48	–
N ₂	28.016	1.28	–
Total	–	100.00	49024.14

steam and that from the cell reaction itself, may cause reforming of the fuel to hydrogen and carbon monoxide in high-temperature fuel cells, such as an MCFC.

The chemical reactions involved in steam reforming of natural gas (Table 2) are



The third being the water–gas shift reaction. Assuming that the higher hydrocarbons participate in hydrocracking reactions, we have



8. Results and discussion

The following considerations were made for the analysis presented.

- A value of 0.65 for the coefficient of performance of the absorption refrigeration system [10].
- A value of 75% of conversion of the anode gas in the fuel cell unit [12].
- The exhaust gases temperature (point 8, Figs. 2 and 3) is fixed at 150 °C [7].
- Steam/carbon ratio of 3.0 [12].
- All gas stream pressure is atmospheric [7].
- A value of 70% for the efficiency of the heat recovery steam generator [10].

Some fixed parameters adopted in evaluating of the co-generation systems are presented in Tables 3 and 4 shows the mass flow rate (m), temperature (T), enthalpy (h), and entropy (s) for the points indicated in Figs. 2 and 3. Tables 5 and 6 show the results of energy and exergy performance, respectively of the co-generation systems proposed.

The parameters of energy and exergy performance showed in Tables 5 and 6 emphasise the importance of

Table 3
Fixed parameters

Parameter	Value
Operation period (h per year)	6000
Fuel cost (US\$/kWh)	0.011
Buying price of electricity (US\$/kWh)	0.090
Temperature in the ambient reference (K)	298.15
Pressure in the ambient reference (MPa)	0.101
Universal gas constant (kJ/kmol/K)	8.314

Table 4
Data for the points indicated in Figs. 2 and 3.

Points	$m_{\text{case 1}}$ (kg/s)	$m_{\text{case 2}}$ (kg/s)	T (°C)	h (kJ/kmol)	s (kJ/kmol/K)
1	0.122	0.122	530	3101.62	13.33
2	0.393	0.393	530	3552.00	8.91
3	1.633	1.633	650	2108.46	14.01
4	2.660	2.660	260	620.12	7.43
5	4.293	4.293	1200	2059.94	9.78
6	4.293	4.293	650	1203.38	9.06
7	3.175	3.175	650	1272.74	9.63
8	3.175	3.175	150	556.49	8.52
9 (case 1)	0.690	14.693	185	2781.00	6.56
9 (case 2)	0.690	14.693	25	104.87	0.37
10 (case 1)	0.690	14.693	185	777.70	2.17
10 (case 2)	0.690	14.693	1	4.26	0.015
11 (case 1)	0.690	–	110	460.57	1.41

Table 5
Results for energy performance

Electric power (E_p , kW)	2928 ^a
Recovered thermal power (E_c , kW)	2274
Fuel thermal power supply (E_F , kW)	5983
Electrical efficiency (η_{el} , %)	48.9
Fuel utilization efficiency (η_{F_3} , %)	86.9

^a includes compressor work.

Table 6
Results for exergy performance

Component	ΣEx_{in} (kW)	ΣEx_{out} (kW)	I (kW)	η_{II} (%)
Compressor	993.90	515.86	478.04	0.52
Combustion chamber	7330.72	4875.20	2445.51	0.67
HRSG	1642.76	964.59	678.17	0.59
ARS	1611.28	395.12	1216.16	0.25
Heat exchanger	10853.8	8382.92	2470.94	0.77
Fuel cell	6275.14	2928.70	3346.43	0.46

analysing both energy and exergy flows. The energy input is relatively close to exergy input which yields an electrical efficiency close to second law efficiency of fuel cell unit. The identification of losses is the primary difference between the energy and exergy balances. Energy was mainly lost in the exhaust gases of the system. It is important to observe that the exergy losses (irreversibilities) due to

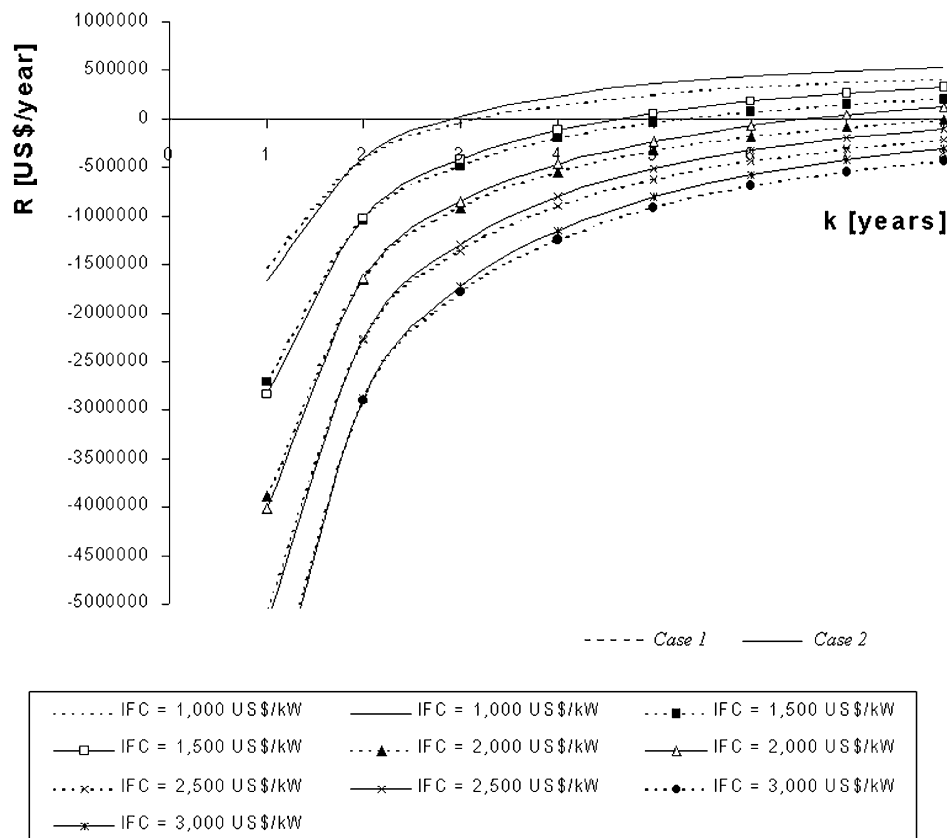


Fig. 4. Total annual savings (R) as a function of the payback period (k).

destruction of exergy in the heat exchanger and combustion chamber account for most of the plant irreversibility. This irreversibility is associated with the maximum temperature of the products.

Fig. 4 shows the annual saving (R) as a function of the payback period (k), considering an annual interest rate of 12% and an investment cost on the fuel cell system ranging from US\$ 1000 to US\$ 3000/kW [6], depending on fuel cell production volume. The economic analysis shown in Fig. 4 displays that fuel cell systems with investment cost between US\$ 1000 and US\$ 1500/kW (for payback values of about 3 and 4 years, respectively) would show technical and economic feasibility. These levels of investment are not far from being realized. It is important to observe that case 2, which has the highest investment cost, offers more economical advantages than the case 1.

9. Conclusions

The high efficiency and lower emission of pollutants in comparison with other technologies makes of the fuel cell co-generation system, an attractive technology for energy generation.

In principle, fuel cells convert the Gibbs free energy of isothermal oxidation of a fuel directly into electrochemical work. But, hydrocarbon fuels must be reformed into hydrogen and other by-products. This process degrades the electrochemical work potential of the fuel. In the molten carbonate fuel cells this effect can be mitigated by recuperation of waste heat. Moreover in the steam reforming process, surplus steam must be supplied to suppress unwanted carbon-forming reactions. This, together with the accumulation of reaction products, dilutes the chemical potential of the fuel.

For the energy and exergy, analyses show that the electrical efficiency of the system was 49% and the second law

efficiency of the fuel cell unit was 46%. Finally, the analysis in this paper shows that fuel cell systems with investment costs between US\$ 1000 and US\$ 1500/kW (for payback values between 3 and 4 years, respectively) would show technical and economic feasibility. These levels of investment are not far off.

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