TECHNICAL AND ECONOMIC ANALYSIS OF A SOLID OXIDE FUEL CELL (SOFC) COGENERATION SYSTEM

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Abstract. This paper presents a methodology for the study of a solid oxide fuel cell (SOFC) cogeneration system applied to a dairy industry. The typical demands are 2,100 kW of electricity, 8,500 kg/h of saturated steam (P = 1.08 MPa) and 2,725 kW of cold-water production (frigorific power). Depending on the recuperation equipment associated, the cogeneration system permits the use of residual heat, for the production of steam, cold water and hot air. In this study, a comparison is made between two configurations of fuel cell cogeneration systems (FCCS). The first configuration uses a SOFC associated to a heat exchangers and heat recovery steam generator (HRSG) and the second one uses a SOFC associated to a heat exchangers and absorption refrigeration system (ARS). The cogeneration system is sized in order to meet the electrical demand of the plant (electrical parity). The plant performance is evaluated on the basis of fuel utilization efficiency and each system component is evaluated on the basis of Second Law efficiency. The presented energetic analysis shows a fuel utilization efficiency of about 87% for the case of using a heat recovery steam generator and of about 83% for the case of using an absorption refrigeration system. The exergetic analysis shows the irreversibilities in the combustion chamber and in the absorption refrigeration system of the plant are more significant. Finally, the economic feasibility study was included for the evaluation of a cogeneration system, taking the payback period, the annual interest rate, the fuel price and the equivalent period of utilization into account.

Keywords *Cogeneration, solid oxide fuel cell, fuel cell cogeneration system, heat recovery steam generator, absorption refrigeration system*

1. Introduction

The beginning of the 21st century has been characterized by the rapid development of environmentally friendly technologies. Global warming combined with public awareness concerning the impact of greenhouse gasses on the environment has triggered the search for new high efficiency technologies of energy supply such as combined heat and power systems or cogeneration systems. These 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 cogeneration applications because they are able to produce high-temperature steam, that can be used to reform a fuel such as natural gas. In this configuration, the fuel cell is optimized to produce maximum thermal efficiency and maximum temperature of the usable heat.

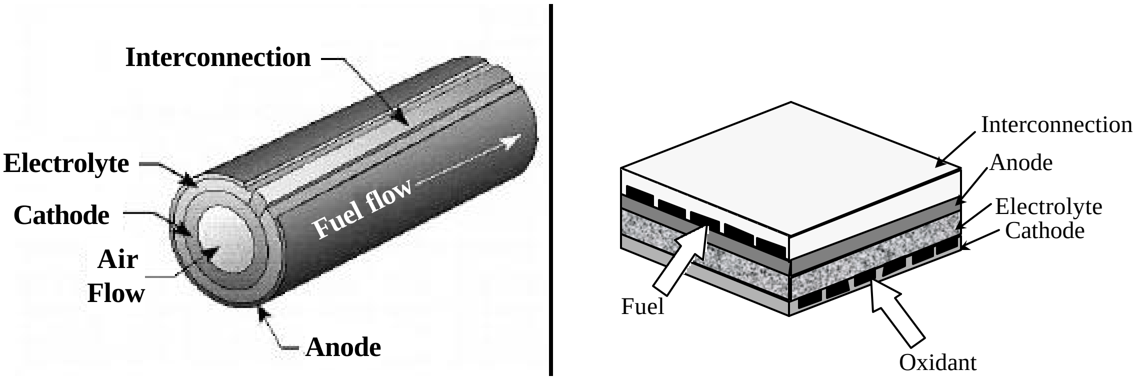
The fuel cell is an energy conversion device that transforms the chemical energy of the fuel directly into electricity without the requirement of energy conversion into heat. When fuel cells produce the entire electrical output, the apparent advantage is the elimination of the limitation of Carnot-efficiency. This fact and the environmental advantages explain the increasing interest in fuel cell systems for power generation. However, the fundamental thermodynamic reason for interest in fuel cell is the reduction of combustion irreversibility.

In this paper, the energy, exergy and economic analyses of two configurations of SOFC cogeneration system applied to a dairy industry are presented. This system uses natural gas and operates on electrical parity. The system can utilize the residual heat recovery for steam production (saturated steam) or an absorption refrigeration system for cold-water production. The plant performance has been evaluated on the basis of fuel utilization efficiency and each component of the system is evaluated in the Second Law Efficiency. The energetic analysis shows a fuel utilization efficiency of about 87% for the case of using a HRSG and about 83% for the case of using an ARS. The exergetic analysis shows the exergy losses (irreversibilities) in the combustion chamber and in the absorption machine are significant. Further, the payback period is determined as a function of the investment level in SOFC cogeneration system.

2. Fuel cell system

Generally, the cogeneration involves the generation of useful heat in addition to electricity. Part of the heat, resulting from irreversible losses, can be recuperated from exhaust gases and also from unoxidized fuel. The most important requirement in this application is the ability to electricity generation and the possibility to produce high-grade heat. The high-temperature fuel cells, such as molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) are most suited because they are able to produce high-temperature steam, normally utilized for the natural gas reform. In these configurations, the fuel cell systems are optimized to produce maximum thermal efficiencies and maximum temperatures of the usable heat (Srinivasan et al., 1999).

The solid oxide fuel cell (SOFC) is also well suited for large-scale industrial power generation. It has the advantage of being more compact than MCFC for a same electrical capacity and has demonstrated longer lifetimes. The SOFC uses ceramic electrolyte (85-90% zirconia with about 10-15% yttria). The SOFC are being developed in demonstration units, mainly, in two different configurations, as shown in Fig. 1.



Tubular

Flat Plate

Figure 1. Main SOFC designs (Larminie and Dicks, 2002).

The ion conducted across the electrolyte is the oxide (O^{2-}) ion. At the cathode, oxygen from the air is combined with electrons (from the anode) to form the oxide ion (Hirschenhofer *et al.*, 1994):

$$\tfrac{1}{2}O_2 + 2e^- \rightarrow O^{2-} \tag{1}$$

The oxide ion move across the electrolyte through the zirconia matrix. At the anode, the oxide ions are consumed by the oxidation of hydrogen to form steam releasing electrons to the external circuit ion (Hirschenhofer et al., 1994):

$$H_2 + O^{2-} \rightarrow H_2O + 2e^- \tag{2}$$

3. Energy requirements

The dairy industry has a medium size and the typical electrical, steam and cold water demands are 2,100 kW, 8,500 kg/h of saturated steam (P = 1.08 MPa) and 2,725 kW (frigorific power), respectively. The last value refers to the cold-water production at 1°C, for the frigorific chamber of the factory.

4. The cogeneration system

A comparison is made between two cogeneration configurations. The first one (case 1) consists mainly of a SOFC associated to a heat recovery steam generator (HRSG), as shown in Fig. 2. The second one (case 2) consists mainly of a SOFC associated to an absorption refrigeration system (ARS), as shown in Fig. 3. Both cases work supplying all the electrical needs of the establishment (electrical parity).

5. Thermodynamic analysis

The energetic analysis of a thermal system is based on the First Law of Thermodynamics with the following two distinct assertions (Utgikar et al., 1995):

- 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 (Dunbar et al., 1991):

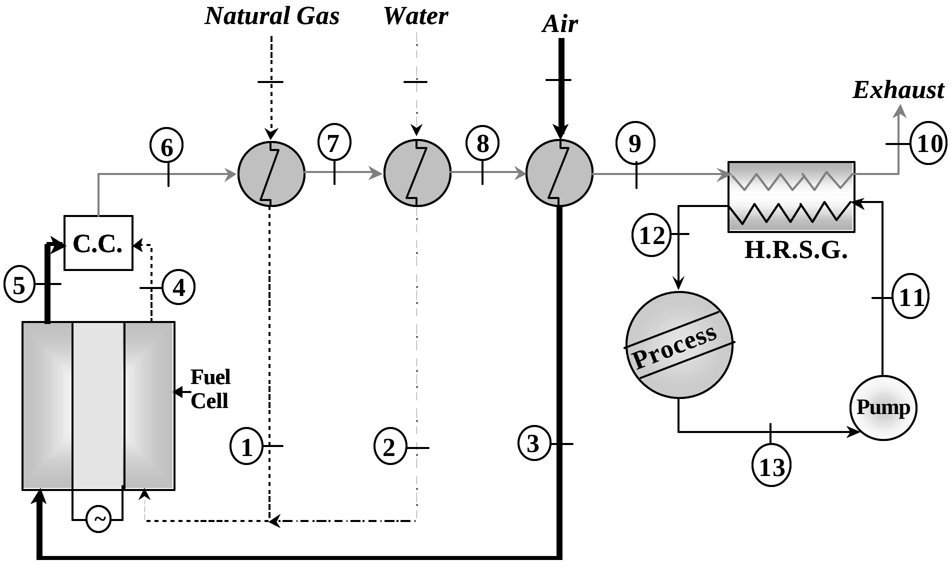
$$\sum_{\text{out}} N_j = \sum_{\text{in}} N_j + N_p \tag{3}$$

Assuming an ideal-gas behavior, the enthalpies may be obtained from (Dunbar et al., 1991):

$$E_i = \sum_j N_{ij} h_j \tag{4}$$

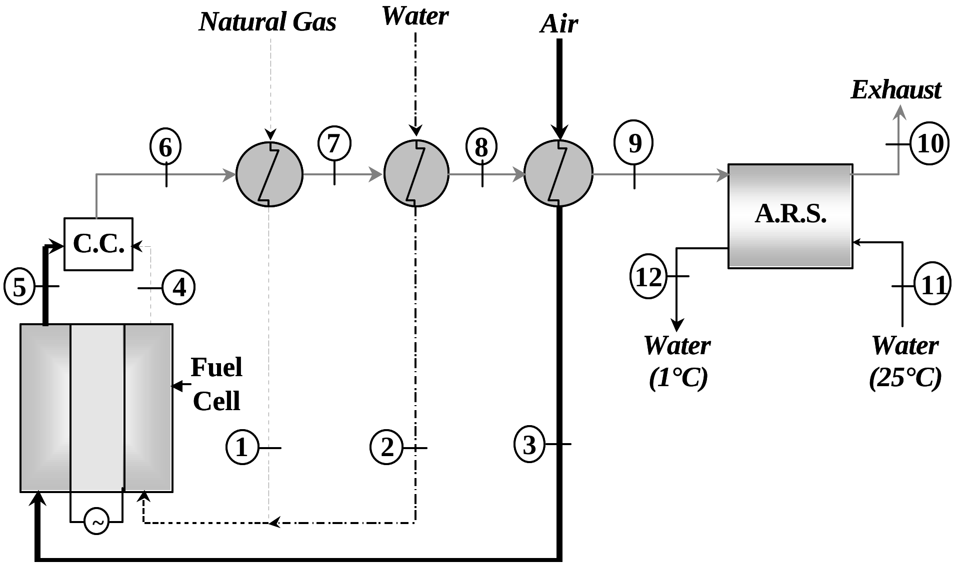
where:

$$h_j = h_0 + \int_{T_0}^{T} Cp_j \, dT \qquad (5)$$



Note: C.C. - Combustion Chamber; HRSG - Heat recovery steam generator

Figure 2. SOFC cogeneration plant (case 1).



Note: C.C. - Combustion Chamber; ARS – Absorption refrigeration system

Figure 3. SOFC cogeneration plant (case 2).

The entropy is (Dunbar et al., 1991):

$$s_j = s_{j0} + \int_{T_0}^{T} Cp_j \,(dT / T) - R_G \ln (P_j / P_0) \tag{6}$$

The exergetic analysis is based on the Second Law of Thermodynamic according to which complete transformation of heat into work is not possible (Utgikar et al., 1995). 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 (Utgikar et al., 1995):

$$ex_i = ex_{TM,i} + ex_{CH,i} \tag{7}$$

$$ex_{TM,j} = \int_{T_0}^{T} Cp_j [1-(T_0/T)]dT + R_G T_0 \ln (P/P_0) \tag{8}$$

$$ex_{CH_j} = h_j(T_0) - T_0 s_j(T_0, P_0) + R_G T_0 \ln \chi_i - \mu_j^0 \tag{9}$$

Finally, the total exergy of stream i is (Dunbar et al., 1991):

$$Ex_i = N_i \sum_j \chi_{ij} \, ex_{ij} \tag{10}$$

The exergetic analysis requires that the environment is defined. The temperature and pressure of the environment were set equal to the reference temperature and pressure (25°C, 1 atm). The atmosphere was modeled as an ideal-gas mixture with the composition shown in Tab. (1) (Bedringås et al., 1997).

Table 1. Mole fractions and chemical exergy of the reference components in atmospheric air (Bedringås et al., 1997).

Component	Mole fraction ($\chi_{0,j}$)	Chemical exergy (kJ/kmol)
N_2	0.7567	691.1
O_2	0.2035	3,946.7
H_2O	0.0303	8,667.9
CO_2	0.0003	20,108.5
Ar	0.0092	11,622.3

The fuel utilization efficiency (η_F) is the ratio of all the useful energy extracted from the system (electrical and process heat) to the energy of the fuel input. Thus (Utgikar et al., 1995):

$$\eta_F = \eta_{el} + \eta_Q = \frac{W_{el} + Q_P}{E_F} \tag{11}$$

The Second Law efficiency of cogeneration 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 (Utgikar et al., 1995):

$$\eta_{II} = \frac{W_{el} + Ex_P}{Ex_S} \tag{12}$$

6. Economic analysis

The economic feasibility for the proposed systems, depends on the electricity, steam and cold-water production costs in the cogeneration systems cover in those for conventional systems. International experience shows that high electricity tariffs encourage investment in cogeneration systems with capacity classes corresponding to those in this study (Leal and Silveira, 2002).

The expressions of specific electricity production cost (C_{EL}), specific steam production cost (C_v) and specific cold-water production cost (C_{CW}) varies from system to system, and may be determined by equations(Leal and Silveira, 2002):

$$C_{EL} = \frac{(I_{PL} - I_{RE}) \cdot f}{H \cdot E_p} + \frac{C_F \cdot [E_F - E_c - (Los / 2)]}{E_p} + CM_{CS} \qquad (13)$$

$$C_v = \frac{I_{HRSG} \cdot f}{H \cdot E_v} + \frac{C_F}{E_v} \cdot [E_c + (Los / 2)] + CM_{HRSG} \qquad (14)$$

$$C_{CW} = \frac{I_{ARS} \cdot f}{H \cdot P_f} + \frac{C_F}{P_f} \cdot [E_c + (Los / 2)] + CM_{ARS} \qquad (15)$$

$$Los = E_F - E_p - E_c \qquad (16)$$

The specific cost of steam production in conventional boiler (C_{vc}) is (Leal and Silveira, 2002):

$$C_{vc} = \frac{I_{CB} \cdot f}{H \cdot E_v} + \frac{C_{oil}}{\eta_B} + CM_{CB} \qquad (17)$$

All costs considering civil installations, electrical equipment, control system, piping and local assembling.

The annual savings due to electric power, saturated steam and cold-water production can be calculated by (Leal and Silveira, 2002):

$$GP_{EL} = E_R .H.(P_{el} - C_{EL}) + (E_p - E_R).H.(PV_{EL} - C_{EL}) \qquad (18)$$

$$GP_v = E_v .H.(C_{vc} - C_v) \qquad (19)$$

$$GP_{PF} = P_f .H.(PE_{PF} - C_{CW}) \qquad (20)$$

The total annual savings is the sum of the annual savings. Related to electricity and steam production (Leal and Silveira, 2002):

$$R = GP_{EL} + GP_v \qquad (21)$$

Related to electricity and cold-water production (Leal and Silveira, 2002):

$$R = GP_{EL} + GP_{PF} \qquad (22)$$

7. Steam reforming of natural gas

According to Gardner (1997), the direct electrochemical oxidation of a hydrocarbon fuel is not a practical option yet. Several chemical reaction pathways, competing with electrochemical oxidation, occur more readily. Some of these lead to unwanted carbon formation and result damage. Steam is added to a hydrocarbon fuel to prevent carbon formation. Depending on the catalytic nature of the fuel electrode, this 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 in MCFC and SOFC.

The chemical reactions involved in steam reforming of natural gas (composition showed in Tab. (2)) are:

$$CH_4 + H_2O \rightarrow 3\,H_2 + CO \qquad (23)$$

$$C_2H_6 + 2\,H_2O \rightarrow 5\,H_2 + 2\,CO \qquad (24)$$

$$C_3H_8 + 3\,H_2O \rightarrow 7\,H_2 + 3\,CO \qquad (25)$$

$$C_4H_{10} + 4\,H_2O \rightarrow 9\,H_2 + 4\,CO \qquad (26)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (27)$$

Equation (27) is the water-gas shift reaction. Assuming that the higher hydrocarbons participate in hydrocracking reactions, we have:

$$C_5H_{12} + 4\,H_2 \rightarrow 5\,CH_4 \qquad (28)$$

Table 2. Natural Gas Composition (Silveira & Tuna, 1999).

Component	Relative molecular mass	% vol	LHV [kJ/kg]
CH_4	16.042	89.35	50,000
C_2H_6	30.068	8.03	47,525
C_3H_8	44.094	0.78	46,390
C_4H_{10}	58.120	0.07	45,775
C_5H_{12}	72.048	0.01	45,400
CO_2	44.009	0.48	-
N_2	28.016	1.28	-
Total	-	100.00	47,966

8. Results and discussion

The following considerations were made for the energetic and exergetic analyses presented:

- A value of 0.65 for the coefficient of performance of the absorption refrigeration system (Petbow, 1991).
- A value of 70% for the efficiency of heat recovery steam generator (Leal and Silveira, 2002).
- A value of 85% of conversion of the anode gas in fuel cell unit (Casanova and Veyo, 2001).
- The stack temperature is fixed at 150°C (Dunbar et al., 1991).
- Steam/carbon ratio of 3.0 (Selman, 1993).
- All gas stream pressure are atmospheric (Dunbar et al., 1991).

Some fixed parameters adopted in evaluating of the cogeneration system are presented in Tab. (3). Table 4 shows the mass flow rate (m), temperature (T), enthalpy (h), and entropy (s) for the points indicated in Figs. (2) and (3). Table 5 shows the results of energetic performance. Tables 6 and 7 show the results of exergetic performance for the cases 1 and 2, respectively.

Table 3. Fixed Parameters.

Parameter	Value
Equivalent period of utilization H [h/year]	7,000
Fuel cost C_F [US$/kWh]	0.011
Buying price of electricity Pel [US$/kWh]	0.08
Temperature in the ambient reference T_0 [K]	298.15
Pressure in the ambient reference P_0 [Mpa]	0.101
Universal gas constant R_G [kJ/kmol.K]	8.314

Table 4. Data for the points indicated in Fig. (2) and (3).

Points	m (kg/s)	T (°C)	*h* (kJ/kg)	*s* (kJ/kg.K)
1	0.09	800	4896.8	18.78
2	0.29	800	4158.0	9.05
3	2.75	507	825.1	7.86
4	0.67	1200	4080.3	18.40
5	2.46	1200	1672.1	8.67
6	3.13	1427	2364.1	9.97
7	3.13	1337	2219.4	9.90
8	3.13	1065	1792.4	9.61
9	3.13	707	1259.6	8.99
10	3.13	150	511.2	8.02
11 (case 1)	0.76	183	777.7	2.17
12 (case 1)	0.76	183	2781.0	6.56
13 (case 1)	0.76	183	777.7	2.17
11 (case 2)	*15.4*	*1*	*4.3*	*0.02*
12 (case 2)	*15.4*	*25*	*104.9*	*0.37*

Table 5. Energetic Performance

	Case 1	*Case 2*
Electric Power [kW]	2,100.0	2,100.0
Recovered Thermal Power [kW]	1,723.0	1,552.5
Power Supply by the fuel based in LHV [kW]	4,392.0	4,392.0
Electrical efficiency [%]	47,8	47,8
Fuel utilization efficiency [%]	87,0	83,2

Table 6. Exergetic Performance (Case 1)

Component	**$\sum Ex_{in}$ [kW]**	**$\sum Ex_{out}$ [kW]**	**I [kW]**	**η_{II} [%]**
Preheater – natural gas	8,636.43	8,428.28	208.14	0.98
Preheater – water	3,954.63	3,313.19	641.44	0.84
Preheater - air	3,056.81	2,539.13	517.68	0.83
Fuel cell	4,898.51	2,100.00	2,798.51	0.43
Combustion chamber	8,641.36	4,333.31	4,308.05	0.50
Heat recovery steam generator	1,826.33	988.27	838.07	0.54

Table 7. Exergetic Performance (Case 2)

Component	**$\sum Ex_{in}$ [kW]**	**$\sum Ex_{out}$ [kW]**	**I [kW]**	**η_{II} [%]**
Preheater – natural gas	8,636.43	8,428.28	208.14	0.98
Preheater – water	3,954.63	3,320.67	633.96	0.84
Preheater - air	3,064.29	2,428.73	635.56	0.79
Fuel cell	4,898.51	2,100.00	2,373.65	0.43
Combustion chamber	8,641.36	4,333.31	4,308.05	0.50
Absorption refrigeration system	1,682.82	427.10	1,255.72	0.25

The parameters of energetic performance show in Tab. (5) emphasize the importance of analyzing the energy flows in the cogeneration system. Energy was mainly lost in the exhaust gas (stream 10). In the case 1, the fuel utilization efficiency was about 87% while in the case 2 this efficiency was about 83%. This behavior is due mainly to the use of an absorption refrigeration system. The parameters of exergetic performance (Tab. (6) and (7)) display that the major destruction of exergy (irreversibility) was in the combustion chamber (which is associated to the maximum temperature of the products) and in the absorption refrigeration system (which is associated to the process that occurs inside the machine).

Figure 3 shows the annual savings (R) as a function of the payback period (k), considering an annual interest rate of 8% and an investment cost on fuel cell system raging from 1,000 to 10,000 US$/kW, according to Brandon and Hart (1999). The investment cost in the absorption refrigeration system was 200 US$/kW (Silveira & Gomes, 1999) and the investment cost in the heat recovery steam generator was set in 120% of the investment in a conventional boiler of the same size.

The economic analysis shows that fuel cell systems with investment cost of 1,000 display a payback values of about 2.5 and 3.0 years for the FCCS with ARS and HRSG, respectively. For the investment cost of 2,000 US$/kW, the payback period are 6 and 7 years for the FCCS with ARS and HRSG, respectively. These levels of investment are not distant for coming years, but in actual level of investment the system using HRSG or ARS is unviable.

9. Conclusions

The high efficiency and lower emission of pollutants in comparison with other technologies makes of the FCCS an attractive technology of power generation.

Ideally, 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 byproducts. 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.

The energetic and exergetic analyses show that the electrical efficiency of the system was about 49% and the Second Law efficiency of the fuel cell unit was about 45%. It is important to observe that frigorific power produced in cogeneration system operating in electrical parity, was not self-sufficient to attempt the dairy industry. Therefore, it is necessary to complement the needs of thermal energy of the industry, by conventional system (electrical chiller).

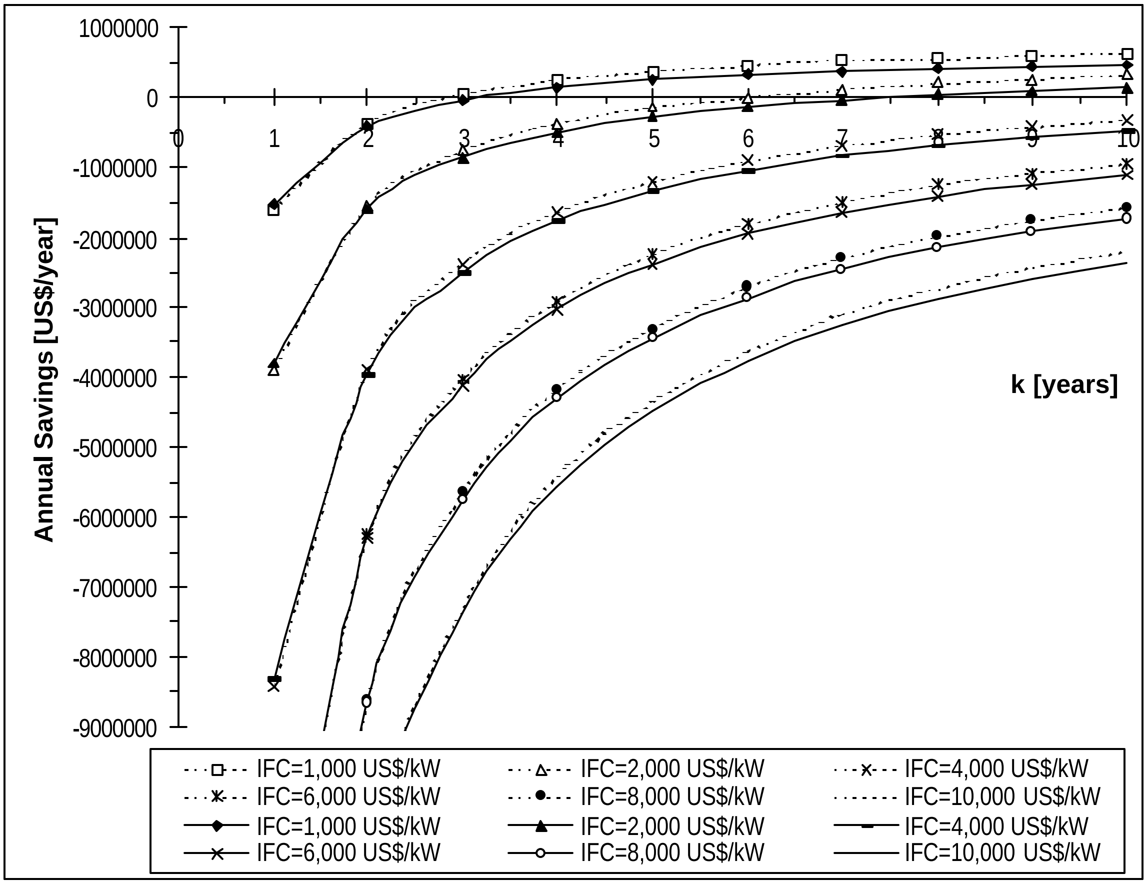


Figure 3 – Total Annual Saving as a function of the payback period (Case 1: continuos line; Case 2: featured line).

Finally, the economic analysis shows that fuel cell systems with investment cost between 1,000 (for payback values of about 2.2 and 2.6 for the FCCS with ARS and HRSG, respectively) and 2,000 US$/kW (for payback values of about 5.2 and 6.2 for the FCCS with ARS and HRSG, respectively) would show economic feasibility. These levels of investment are not distant for coming years, but in actual level of investment the system using HRSG or ARS is unviable. It is very important to consider the benefits of the reduction of emission of pollutants (environmental advantages) in economic analysis. We recommend a development of a methodology including "energo-environmic" and "exergo-environmic" analysis of the FCCS.

10. Acknowledgement

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11. Nomenclature

Cp	Molar specific heat [kJ/kmol.K]
C_F	Fuel cost [US$/kWh]
C_{CW}	Specific cold-water cost [US$/kWh]
C_{EL}	Specific electricity cost [US$/kWh]
CM	Maintenance cost [US$/kWh]
C_{oil}	Oil cost [US$/kWh]
C_v	Specific saturated steam cost [US$/kWh]
E	Energy flow [kW]
E_c	Recovered heat flow [kW]
E_F	Thermal power supplied by the fuel [kW]
E_p	Electricity produced in the cogeneration system [kW]
E_R	Electricity required by the building [kW]
ex	Specific exergy [kJ/kmol]
Ex	Exergy flow [kW]
Ex_P	Exergy flow related to process heat [kW]
f	Annuity factor [1/year]
GP_{EL}	Annual saving for the electricity production [US$/year]
GP_{PF}	Annual saving for the cold-water production [US$/year]
GP_v	Annual saving for the saturated steam production [US$/year]
h	Specific enthalpy [kJ/kmol]

h_0	Specific enthalpy in the ambient reference [kJ/kmol]
H	Operation period [h/year]
I	Equipment investment [US$]
I_{PL}	Total plant investment [US$]
k	Amortisation period [years]
Los	Energy losses in the cogeneration 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	Frigorific power [kW]
PV_{EL}	Sale tariff of the electricity surplus [US$/kWh]
Q	Heat transfer rate [kW]
R	Total annual saving [US$/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 [-]
η_{el}	Electricity production efficiency [-]
η_Q	Thermal efficiency [-]
μ^0	Electrochemical potential in the ambient reference [kJ/kmol]

Subscripts

ARS	Absorption refrigeration system
CH	Chemical
CB	Conventional boiler
CS	Cogeneration system
el	Electrical
F	Fuel
HRSG	Heat Recovery Steam Generator
P	Process
RE	Recuperation equipment
S	Supplied
TM	Thermal mechanical

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