EXERGOECONOMIC ANALYSIS OF A SOLID OXIDE FUEL PROTOTYPE OF 2 KW

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Abstract

The energy analysis, based on the first law of thermodynamics, has been constituted one of the most used tools for evaluating the efficiency of energy systems. However, as this type of analysis does not consider capacity to do work, a correct evaluation of the quality of energy involved in the process is compromised. The exergy analysis is to evaluate the system using the First and Second Law of Thermodynamics. This procedure can calculate the losses that occur in the system and the power that is actually obtained in the process by evaluating the energy in the qualitative aspect. The exergetic analysis in co-generation plants and generation ones are used in order to gain greater efficiency in combustion processes and reuse of wastes. The system of power and heat generation under study consists of a solid oxide fuel cell of 2 kWe connected to a heat exchanger, which recovery the energy from the production of electric power carried out at high temperatures to produce hot water for cleaning. The economic analysis was developed with the aim of studying the economic feasibility of the system including cost calculations on exergy basis of electric power generated and hot water produced. This analysis shows the values of exergy flows associated with the system, locating and quantifying the qualitative losses and irreversibilities of the components, as well as its exergetic efficiency. The exergoeconomic study quantify the costs of these flows based on methods available in the literature and considering the cost of fuel consumed by the SOFC unit. This study aims to facilitate the construction of a solid oxide fuel cell prototype of 2 kWe. For this purpose, it is important to know the maximum amount of useful energy possible to obtain and to quantify the losses and irreversibilities. The study also identifies the effect of temperature system on the level of irreversibility and over the efficiency of fuel cell and heat exchanger as a one.

Keywords: Solid Oxide Fuel Cell; Exergoeconomic Analysis; Thermoeconomics; Exergy; Energy Efficiency.

1. INTRODUCTION

The use of fossil fuels is the main source of energy today, oil and coal fuels are still the most used around the world. But over the years these fuels are becoming increasingly scarce and, moreover, are fuels that emit pollutants into the atmosphere.

The need to reduce the environmental impacts caused by the emission of pollutants has stimulated the development of new technologies that have high energy efficiency and small emissions. In this context the fuel cells appear as an option, because they are power generation devices that use hydrogen-rich gases as an energy. Fuel cells have a good efficient and low emission of pollutants. (SOUZA,2010)

However, the main reason why fuel cells are not yet widespread is the fact they are not economically competitive at the momment.

One way to reduce your cost is the optimization of fuel cell systems. This is possible through research related to improvement methods. The use of analysis based on laws of thermodynamics in order to better efficiency can result in lower costs and thus greater participation of these devices on the market.

This article aims from an exergy analysis to present the values of exergy flows associated with the system, locating and quantifying the losses and irreversibilities qualitative components, and its exergetic efficiency. The study aims to quantify the costs of these flows based on methods available in the literature that consider the cost of fuel entering the SOFC unit.

2. DESCRIPTION OF THE COGENERATION SYSTEM SOFC-HE

The cogeneration system of Figure 2.1 was constructed using a Fuel Cell Solid Oxide (SOFC) of 2kW and a Heat Exchanger (HE).

The SOFC was constructed from ceramic materials (metal oxides) and metals, so it has the peculiarity of working at high temperatures. This fact gives us the opportunity to harness the heat from the cell. In this system this heat is used to heat water at ambient temperature.
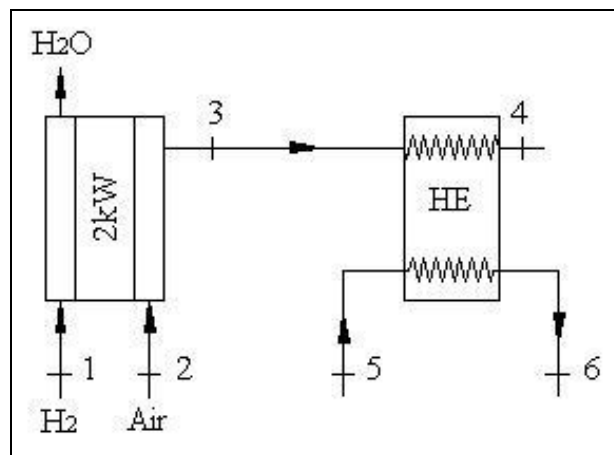

Figure 2.1. Outline of cogeneration system SOFC- HE.

The points in Figure 2.1 represent the flows of the system:

1) Fuel inlet (pure hydrogen gas);
2) Air inlet (oxygen source);
3) Output of high temperature gases (water steam and nitrogen gas)
4) Exhaust gases;
5) Water inlet at ambient temperature;
6) Hot water outlet.

3. EXERGETIC ANALYSIS

3.1 Exergy Concepts

The energy manifests in different forms and each one has its respective characteristics and quality. With power being a property of a system in accordance with the First Law of Thermodynamics, and this cannot be destroyed (conservation of energy), each transformation has a missing part, ie a portion that is not used for work.

Therefore, (RANT, 1956) proposed the word Anergy to denote the energy that cannot be used. Thus, can be describe that energy is the sum of the portion of everything that can be leveraged (exergy) plus the portion that cannot be used (anergy), as summarized in equation (3.1):

$$Energy = Exergy + Anergy \tag{3.1}$$

To calculate the exergy of a system, it is necessary to define a reference for evaluating the maximum work possible to be produced by a system.

Thus, one can also define exergy as a measure of the degree of separation between the system and its environment or reference state. This measure means the maximum work that can be obtained from the system in its interaction with the environment until equilibrium.

3.1.1 General Aspects of Analysis by the First Law of Thermodynamics

The analysis of systems and processes for the first law of thermodynamics is based on conservation of energy and mass. The equations for the volume control on permanent regime, in general, ignore the variations in kinetic and potential energy and can be expressed by (BRANCO, 2005):

$$\sum \dot{m}_e - \sum \dot{m}_l = 0 \tag{3.2}$$

$$\sum \dot{Q}_{cv} - W_{cv} + \sum \dot{m}_e h_{ent} - \sum \dot{m}_l h_{out} = 0 \tag{3.3}$$

where:

$\dot{m}_e$ - Mass flow entering the control volume (kg/s);

$\dot{m}_l$ - Mass flow leaving the control volume (kg / s);

h_{ent} - Specific enthalpy at the entrance of the control volume   (kJ/kg);

h_{out} - Specific enthalpy at the outlet of the control volume   (kJ/kg);

$\dot{Q}_{cv}$ - Heat transfer rate to the control volume (kW);

W_{cv} - Power refers to control volume (kW).

Equation (3.2) indicates that the mass flow entering the control volume equals the mass flow leaving the control volume.

Equation (3.3) states that the total rate of energy entering the control volume is equal to the total rate of energy leaving the control volume, since ignoring the variations in kinetic and potential energy.

3.1.2. General Aspects of Analysis by the Second Law of Thermodynamics

The irreversibilities in a process are quantified by the Second Law of Thermodynamics, through the property called entropy. For cases in a control volume, the equation of entropy is defined as (BRANCO, 2005):

$$\dot{S}_{gen} = \frac{dS}{dt} - \sum_{i=0}^{n} \frac{\dot{Q}_i}{T_i} - \sum_{in} \dot{m}s + \sum_{out} \dot{m}s \geq 0 \tag{3.4}$$

Where:

$\dot{S}_{gen}$ - entropy rate generated in the control volume (kW/K);

$\dfrac{dS}{dt}$ - change of entropy rate (kW/K);

$\displaystyle\sum_{i=0}^{n}\dfrac{\dot{Q}_i}{T_i}$ - entropy rate generated by heat flows (kW/K);

$\displaystyle\sum \dot{m}s$ - entropy rate in and out with the mass flows in the control volume (kW/K).

The balance equation of entropy can be used to predict whether any process that involves interactions of energy may occur, or even if the directions of heat transfer processes are possible. You can also say that the Second Law governs the limits of conversion between different forms of energy.

3.2 Exergy Analysis Methodology

The analysis of the system described in Figure 2.1, was carried from the following information:

• Hydrogen gas as fuel and atmospheric air as an oxidant;
• Ratio air / hydrogen 29.6 (SANTOS, 2005);
• Temperature of exhaust gases 700, 800, 900 and 1000 ° C;
• Reference temperature 25 ° C and atmospheric pressure of 1 atm;
• Air used with the composition given in Table 3.1.

Table 3.1: Molar fraction and standard chemical exergy of atmospheric air components.

Component	Molar fraction $x_{0,i}$	Standard Chemical Exergy, ex_i (kJ/kmol)
N_2	0.79	691.1
O_2	0.21	3946.7

For mixtures of air and fuel must be done in a mixture of excess fuel to obtain maximum power. This mixture is necessary because of the vaporization of the mixture, so the ratio was set at 29.6 air / hydrogen in this experiment. (SANTOS, 2005)

3.2.1 Values of exergetic flows associated with the system

In order to calculate the exergy flows of the system was used the following equation:

$$\dot{Ex} = (\dot{m}_{species})(ex_{species}) \tag{3.5}$$

For the proposed system the exergetic fractions corresponding to kinetic and potencial exergy were disregarded. We then get the following equation for the analysis of the proposed system (equation3.6):

$$ex_{species} = (h_i - h_O) - T_O(s_i - s_O) + (\frac{ex^Q}{PM}) + RT_O \ln(\frac{P_i}{P_O}) \tag{3.6}$$

For the case of perfect gas is used the equation 3.7:

$$ex_{PH} = c_p.(T - T_0) - T_0(c_p.\ln\frac{T}{T_0} - R.\ln\frac{P}{P_0}) \tag{3.7}$$

Where:

$\dot{Ex} = $ Total exergy flow.

$\dot{m}_{species} = $ Mass flow of species (Air, H2, exhaust gas or water)

$ex_{species}$ = Total exergy of the species.

And:

ex_{PH} = Physical exergy of the species

ex_{CH} = Chemical exergy of the species

3.2.2 Method for calculating the exergetic flows of the fuel cell components.

An important parameter to be observed in the exergy analysis is the irreversibility in each device, and consequently in the whole system. The irreversibilities are determined by applying the exergy balance, described in Equation (3.5) in each control volume defined in the system.

The irreversibility shows the amount of exergy that is destroyed ,ie show how the equipment is effective in taking advantage of the exergy that it is introduced.

The exergy balance can be described by: (Ishihara et al,2004):

$$ex_{in} = ex_{out} + ex_{dissipated} + ex_{destroyed} \tag{3.8}$$

$$ex_{dissipated} + ex_{destroyed} = ex_{in} - ex_{out} = ex_{lost} \tag{3.9}$$

Thus, the irreversibility of a component is quantified by the difference between the inflows and outflows, or the flow of exergy lost (ex_{lost}), equation 3.10:

$$\dot{I} = \sum_{I=1}^{N} \dot{Ex}_{in} - \sum_{I=1}^{N} \dot{Ex}_{out} \tag{3.10}$$

However, the cell performs a work, in which case represents the power of the cell, so for the SOFC component was used the equation 3.11:

$$\dot{I} = \sum_{I=1}^{N} \dot{Ex}_{in} - \sum_{I=1}^{N} \dot{Ex}_{out} - W_{SOFC} \tag{3.11}$$

3.3 Results and Discussion

The chemical exergy used for the calculations are shown in Table 3.2.

Table 3.2 – Standard Exergy for the substances involved in the system (SILVEIRA, 2003)

Substance	Standard Chemical Exergy (kJ/kg)
Atmospheric Air	47.65
H_2	120900
H_2O	481.14
N_2	24.67
O_2	123.34

3.3.1 Analysis of the effect of temperature and pressure in the system components

For the calculation of irreversibilities of the system the temperature of operation was varied from 700 to 1000 ° C. From these temperature variations the graph of Figure 3 was built. 1t contains the exergy input and output and the irreversibility of the system.
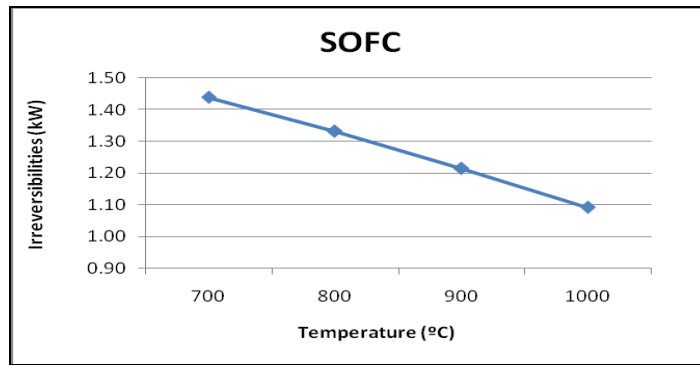
Figure 3.1: Irreversibility vs. Temperature operation of the fuel cell system.

It is observed in Figure 3.1 that the system temperature is inversely proportional to the irreversibility, and for a temperature increase has been a decline in loss (irreversibility) for the fuel cell (SOFC).
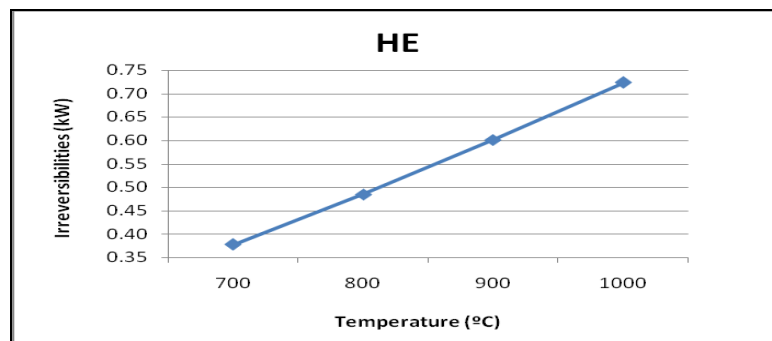

Figure 3.2: Irreversibility vs. operating temperature of the heat exchanger.

For the heat exchanger (Figure 3.2) the operating temperature has the opposite effect of the fuel cell and for an increase in temperature increase to the losses in the heat exchanger.
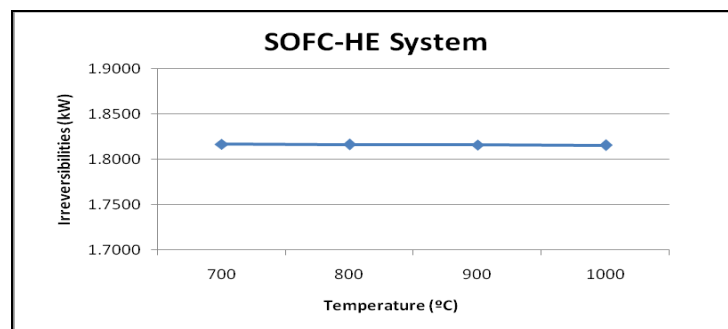

Figure 3.3: Irreversibility vs temperature operation of the system (SOFC + heat exchanger).

Considering the losses of the cell and the heat exchanger is observed that there is a tradeoff causing no major influence of temperature when is considered the system as a whole, this effect is shown in Figure 3.3

3.4.1 Analysis of irreversibility and exergetic efficiency in relation to output water temperature of the Cogeneration System

To perform the analysis of irreversibility and exergetic efficiency of the Cogeneration system the output water temperature ranged between 40 and 80 ° C, and were also considered situations where the efficiency of the heat exchanger ranged between 60% and 90%.

For the calculation of irreversibility equation 3.11 was used and calculate the exergetic efficiency were used equations 3.12 and 3.13 (LEAL, 2003):

$$\Psi = \frac{\text{Products}}{\text{Inputs}}$$

(3.12)

$$\Psi = \frac{\dot{E}x_6 - \dot{E}x_5}{\dot{E}x_3 - \dot{E}x_4} \qquad (3.13)$$

Thus, graphs of Figure 3.4 and Figure 3.5 were generated, the first refers to the analysis of irreversibility while the second comes from the analysis of exergetic efficiency.
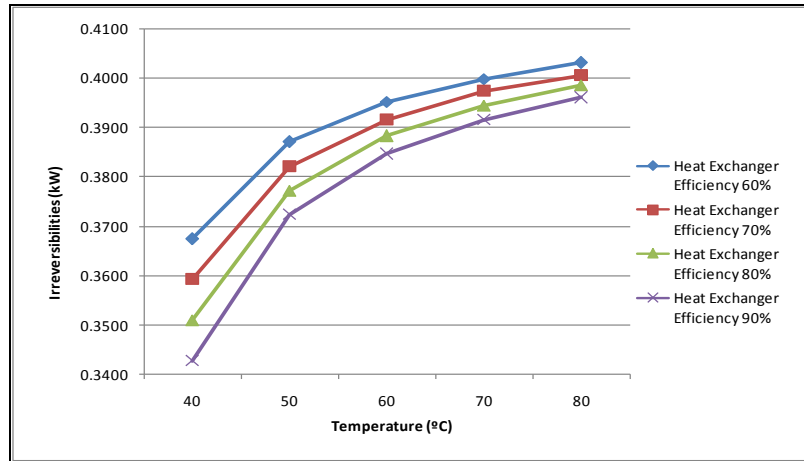

Figure 3.4: Irreversibility as a function of the water output temperature and efficiency of the heat exchanger.
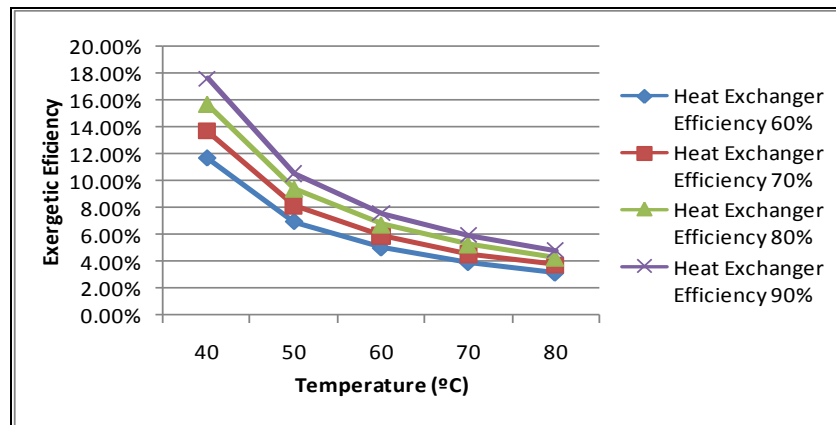

Figure 3.5: Exergetic efficiency as a function of the water output temperature and efficiency of the heat exchanger.

By analyzing the graph of Figure 3.2 we observe that the outlet temperature of water has great influence on the results of irreversibility, so that there is a significant increase in losses between an outlet temperature and other. The curves show a similar shape and that with increasing the temperature, the losses tend to stabilize at a value (close to 0.4 kW). The efficiency of the heat exchanger mainly affects the first point (40 ° C) making for greater efficiencies of the heat exchanger there are wide variations of irreversibilities between one point to another.

The effect of temperature and efficiency of the heat exchanger generates a decrease in the exergetic efficiency. The efficiency of the heat exchanger has a large effect on the first point as well as in the graph of Figure 3.4 the exergetic efficiency tends to stabilize.

Exergetic efficiency and irreversibility are parameters inversely proportional, and while irreversibility increases there is a decrease in the exergetic efficiency. This reasoning becomes clear when thinking about that when we lower the losses in a system there is a greater use of inputs and thus gives a higher efficiency.

The explanation for these effects in the graphs of Figures 3.4 and 3.5 is that by increasing the efficiency of the heat exchanger there is an increased amount of water that can heat up, this increase in mass flow of water causes an increase in physical exergy (or thermomechanical) of the hot water outflow which in turn reduces losses and increases the exergetic efficiency. By lowering the temperature of the water leaving the heat exchanger that can warm a larger amount of water as it will require less energy, increasing the mass flow of water there is an increase in physical exergy, which reduces losses and increases in the system exergetic efficiency.

4. THERMOECONOMIC ANALYSIS

4.1 Theory of Exergetic Cost

For a system operating at steady state can exist a number of flows in and out, and interactions of heat and working with its surroundings. Associated with these transfers of mass and energy are the exergy transfers into or out of the system and the exergy destruction caused by irreversibilities within the system (BRANCO,2005).

Since the exergy measures the real value of such thermodynamic effects and costs should only be attributed to the products that have value, it is significant to use exergy as a basis for assigning costs in thermal systems.

Thermoeconomics relies on the fact that exergy is the only rational basis for assigning costs to the interactions that a thermal system experiences with its environment and the sources of inefficiencies within the same, referring to this approach as "analysis of exergetic cost ". Thus, for this analysis was used the exergetic basis, using the costs of the values of exergetic flows in the system. According to TUNA (1999), the exergetic cost for electricity production can be defined for the equation 4.1:

$$C_{El} = \frac{C_{H2}.\dot{m}_{H2}.e_{H2} - C_{H2}.\dot{m}_3(e_3 - \frac{1}{2}e_4)}{Ep} \tag{4.1}$$

And the exergetic cost for hot water production can be defined by the equation 4.2:

$$C_{HW} = \frac{C_{H2}.\dot{m}_3.(e_3 - \frac{1}{2}e_4)}{\dot{m}_6.e_6} \tag{4.2}$$

The exergetic flow of point 4 (e_4) on the exhaust gases was equally divided between the costs for Electric Power (C_{EL}) and production of Hot Water (C_{HW}) since this flow was used to produce power and hot water and it should be considered.

The Income (INC) generated by the system can be obtained by the equation 4.3:

$$INC = (C_{El} - T_{El}.CCF)H.Ep + (C_{HW} - C_{HW\text{-}NG})H.\dot{m}_6.e_6 \tag{4.3}$$

4.2 Results of the thermoeconomic analysis

For this study was considered the following parameters:

- H = 6000 h / year of system use (equivalent to a run of 290 days per year, 24 hrs / day);
- 0.05 US\$/kWh to the cost of pure hydrogen gas (FLORIDA SOLAR ENERGY CENTER,2007)
- For the value of investment in the heat exchanger (I_{HE}) was adopted 1000 US\$ and for the Fuel Cell (I_{FC}) was used 5000 US\$/kW;
- The amortization period (k) ranged from 1 to 10 years;
- Interest rate (r) fixed at 12%;
- Value of 304.38 R\$/MWh to the tariff of electricity (T_{El}) from the local dealer for a monthly consumption above 200 kWh and 233.88 R\$/MWh for the value of industrial consumption. Values based on tariffs in December 2010. (ANEEL,2010)
- 1.80 R\$/US\$ for the currency conversion factor (CCF)
- 12.90 R\$/m^3 for the cost of heating water $(C_{HW\text{-}NG})$ at room temperature to 40 ° C using Natural Gas. (FORUM COGEN/CANAL ENERGIA,2010)
- Efficiency of the heat exchanger at 90% and hot water output at 40 ° C.

From these parameters and varying the value of the fuel cell in 2500, 5000, 7500 and 10000 US\$ / kW was generated graph of Figure 4.1 to the local consumption and was generated the graph of Figure 4.2 to the industrial consumption:
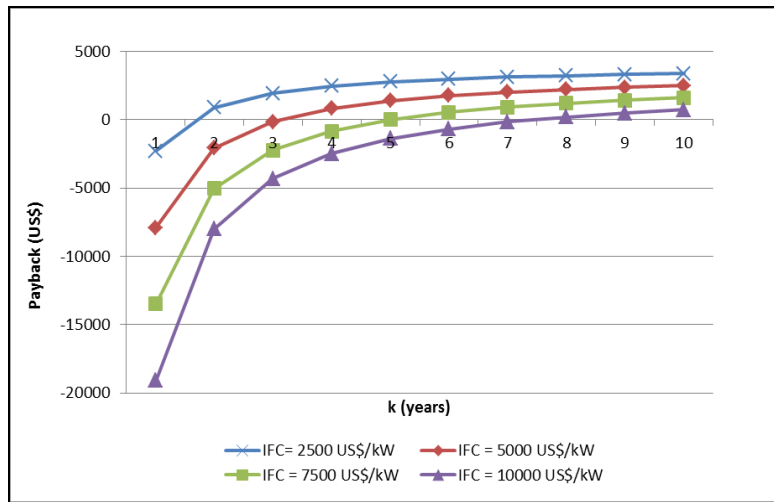
Figure 4.1: Graph payment vs. amortization period (k) "Payback" for different values of investment in the fuel cell considering a local consumption.
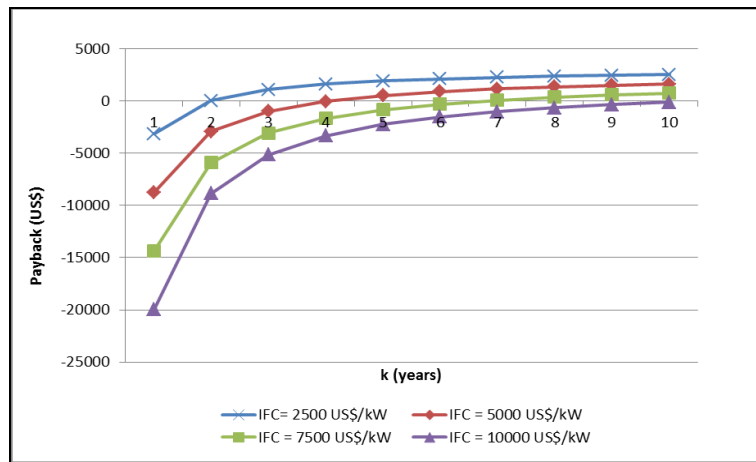

Figure 4.2: Graph payment vs. amortization period (k) "Payback" for different values of investment in the fuel cell considering a industrial consumption.

Considering the values above and analyzing the results for different values of the cost of hydrogen 0.02, 0.05, 0.10 and 0.20 US$ / kW were obtained the graph of Figure 4.3 to local consumption and the graph of Figure 4.4 to the industrial consumption:
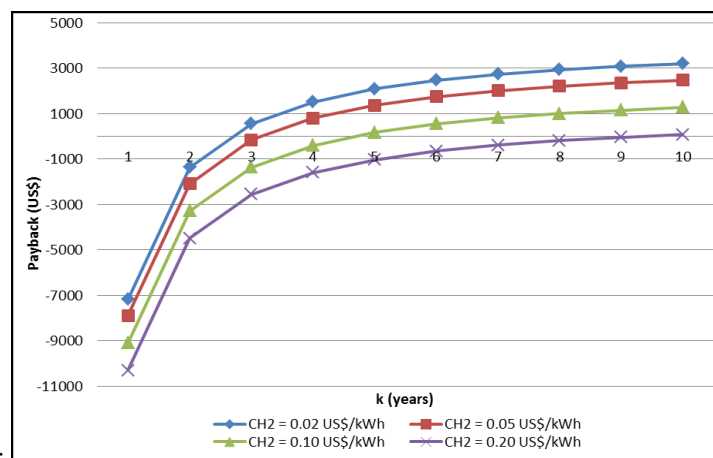

Figure 4.3: Graph payment vs. amortization period (k) "Payback" for different values of cost of hydrogen considering a local consumption
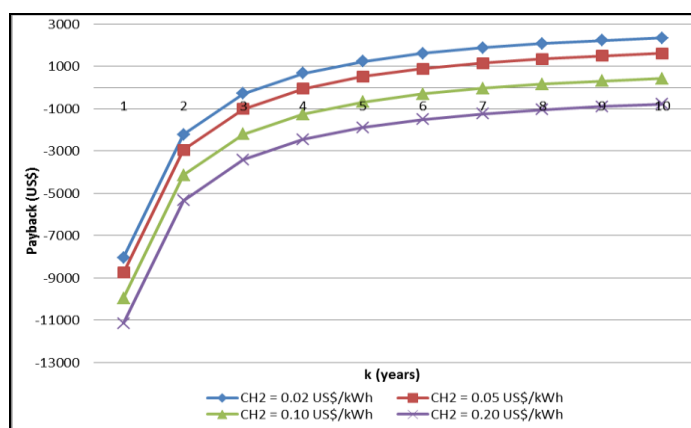
Figure 4.4: Graph payment vs. amortization period (k) "Payback" for different values of cost of hydrogen considering a industrial consumption

5. CONCLUSIONS

The exergy analysis performed concluded that the temperature has no significant effect on the level of irreversibility of the SOFC-CT system, since there is a compensation of the losses when you consider the cell and heat exchanger together.

Considering investments to expected values in today's market, the results showed a depreciation of the investment of three years for residential systems, which can be considered an acceptable time period for the return of such investment. Assessing the most pessimistic scenarios, with higher acquisition costs of fuel cells and hydrogen as fuel, have been an increase in the amortization period of investment for up to six years. For most optimistic scenarios, that may happen by the large number of researches being carried out in fuel cells and hydrogen production, a decrease, in the near future, of these costs is expected, transforming these systems into a viable option for the production of various forms of energy.

Applying this system for industrial use lower income values were obtained and consequently a greater period of depreciation, these results are consequence of the lower values of industrial electricity tariffs. But if we evaluate that the industrial use requires more power, requiring more fuel cells, the value of the investment may be less and thus the system may become viable for industrial purposes.

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