ENERGETIC EVALUATION OF A NATURAL GAS POWERED FUEL CELL-BASED COGENERATION SYSTEM

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Abstract. *Power systems based on fuel cells have been considered for residential and commercial applications in energy Distributed Generation market as these systems can minimize their acquisition, installation and operation high costs. In this work we present an energetic evaluation of a power generation system formed by a 5 kW proton exchange membrane fuel cell (PEMFC) unit and a natural gas reformer (fuel processor) for local hydrogen production. The energy generation system is able to operate with both gases (hydrogen and oxygen from cylinders) as with hydrogen produced from the catalytic steam reforming of natural gas and ambient air, producing electricity (in DC and AC modes) and waste heat energy, which is recovered for use in the water heating. The energetic performance analysis developed simultaneously the energy and economic viewpoints and enabled the determination of the best technical and economic conditions of this energy generation power plant, and the best operating strategies, enabling the optimization of the overall performance of the stationary cogeneration fuel cell unit. This study was made using empirical and phenomenological approaches at full load and partial load and the electrical and thermal efficiency analysis were compared with results available in literature. It was determined the electrical performance of the cogeneration system in function of the design and operational power plant parameters. Additionally, it was verified the influence of the activation conditions of the fuel cell electrocatalytic system on the system performance. It also appeared that the use of hydrogen produced from the natural gas catalytic reforming provided the system operation in excellent electrothermal stability conditions resulting in increase of the energy conversion efficiency and of the economicity of the cogeneration power plant. The results indicate that the fuel cell-based power generation system can operate with potential per single fuel cell of the order of 0.60 V or higher throughout the power range of the system and the efficiency of the generation system is almost stable for electric power to more than 1.5 kW, with electrical efficiency peak of 38%.*

Keywords*: Fuel Cell, PEMFC, Natural Gas Reforming, Distributed Generation*

1. INTRODUCTION

The contemporary world is crucially dependent on electricity and, according to the works of Kotamarty *et al.* (2008) and Blanchette (2008), with the continued socio-economic development at national and global scales, this dependency only tends to increase, along with increasing demands for quality and reliability of the electricity supply, and concern to minimize losses and costs of transmission and distribution of electric energy, than to huge losses which may arise from failures in the supply of electricity.

In this global scenario, the distributed generation (DG) of electric power has received much attention, especially in markets which energy demands are characterized by search for high efficiency and quality, small-size generation and with lower environmental impacts. The economic benefits of the distributed generation may be associated to postponing of the substantial investments in centralized generation and mainly in the expansion of the transmission and distribution networks to follow the increasing demand (Bayod-Rújula, 2009). Among the main DG technologies, the fuel cells should occupy a position of prominence, in the medium and long term, as a result of their cost reduction (Zoulias and Lymberopoulos, 2007). Parallelly, in the current global energy scenario, the natural gas (NG) has been continuously valorized to applications in power generation, such as fossil fuel with lower environmental impact on emissions of greenhouse effect gases. In this sense, the NG has been considered as a transition fuel for the establishment of the Hydrogen Economy, due to its higher hydrogen/carbon ratio when compared to oil, its derivatives and coal (Mancarella and Chicco, 2009). Thus, as discussed by Serra *et al.* (2005), the use of natural gas in fuel cell-based power generation systems, either directly in high-temperature fuel cells, or indirectly through the production of hydrogen in fuel processors (reformers) has been widely considered.

Radulescu *et al.* (2006) studied a combined heat and power system (4.5kWe) formed by a PEMFC (Proton Exchange Membrane Fuel Cell) coupled to a natural gas reformer concluding that, for the configuration studied, the high electric losses and the energy to the need of vaporizing excess water for the fuel-reforming process result in significant reduction of efficiency of the system. However, Chu *et al.* (2008) also studied a PEMFC-3kWe unit running with natural gas and showed the importance of the system integration for the power generation with high efficiency. Moreover, Echigo *et al.* (2004) evaluated the performance of one of the first natural gas reformers for small-scale systems for applications with stationary power generation fuel cells and reported that the system studied was shown to be quite stable, with carbon monoxide (CO) concentration below 1 ppm in the hydrogen-rich gas product were achieved under all partial load operations.

This paper aims to present an energetic evaluation and performance analysis of a power cogeneration system constituted by a 5kWe PEMFC and a natural gas steam reformer, as shown in Figure 1, available in CEPEL (Electric Power Research Center, Brazil) Fuel Cell Laboratory, developed under the CelComb Project (2003-2004 ANEEL R&D Programme) made to the CHESF (São Francisco Hydroelectric Company), according to technical research report deposited in the CEPEL's library (Furtado *et al.*, 2009).

2. EQUIPMENTS AND METHODS

All electrical and thermal tests presented and discussed in this work were obtained from the operation of the 5kWe PEMFC-Natural Gas Reformer power cogeneration system shown in Figure 1, under stable operating conditions, in steady state regime, stayed two minutes in each condition of voltage (U, potential) and electric current (I), through the coupling of an adjustable electric charge, which was used to simulate the condition of a hypothetical consumer. All subsequent results are averages and error bars were used (as was the case, depending on the scale used) to represent the variation of the parameter considered in relation to its average value. A 5kWe PEMFC (Electrocell Company, Brazil) unit is constituted by a stack, formed by 90 single PEM fuel cells (area of 380 cm^2), and a set of auxiliary systems to process, monitoring and control, to ensure the establishment of appropriate conditions for the functioning of the unit, especially as regards the humidification conditions of the gases and of the polymer electrolyte, and the hydrothermal management of the stack.

Figure 1. Different views of the Distributed generation 5kWe PEMFC-NG Reformer power cogeneration system.

The modularity and the integration degree of the total configuration, and its battery bank, allow minimize to downtime for maintenance, characteristic problem of conventional generators. The generation system can operate with isolated loads or not (grid-connected) without loss of performance and accredit the system for applications where the supply of electricity is very critical, especially with regard to requirements for reliability and quality, including harmonic distortion, such as to replace the UPS (uninterruptible power supply) systems and no-breaks.

The natural gas reformer (FPM60-NG Model) was acquired from the IdaTech Company (Bend, Oregon, USA) and it produces hydrogen from catalytic steam reforming of the natural gas, being able to produce up to 65 l/min of H_2 (at 2 psi), with a consumption of 30 l/min of NG at 20-50 mbar and a maximum of 4.8-5.0 l/h of deionized water. The reformer uses a palladium membrane system for purification of the reformed gas, allowing the supply of hydrogen with maximum impurities of the order of 0.5-1.0 ppm of CO, 1.8-3.0 ppm CO_2 and about 180 ppm of CH_4 (nominal design characteristics). The monitoring of the chemical composition of the reformed gas is made by a gas chromatography online system (TRACE GC Ultra, Thermo Scientific). The NG feed flow and hydrogen generated flow were monitored by the computer system reformer added and were confirmed from the results obtained in suitable external mass flow meters (MKS Instruments) calibrated for the respective gases. The discrepancies between the values obtained by both measurement systems was in general small, about 1.5%. But according to the higher reliability, the values used in this work were those obtained with external meters.

3. RESULTS AND DISCUSSION

Figure 2 shows results on the performance of the natural gas reformer. The "Percentage of utilization of the reformer (%)" parameter refers to that percentage of its nominal hydrogen production capacity it is actually operating. In relation to this parameter are presented the flow rates of consumption of NG and deionized water, hydrogen production flow rate, and average energetic conversion efficiency, determined on the basis of their lower heating values (LHV).

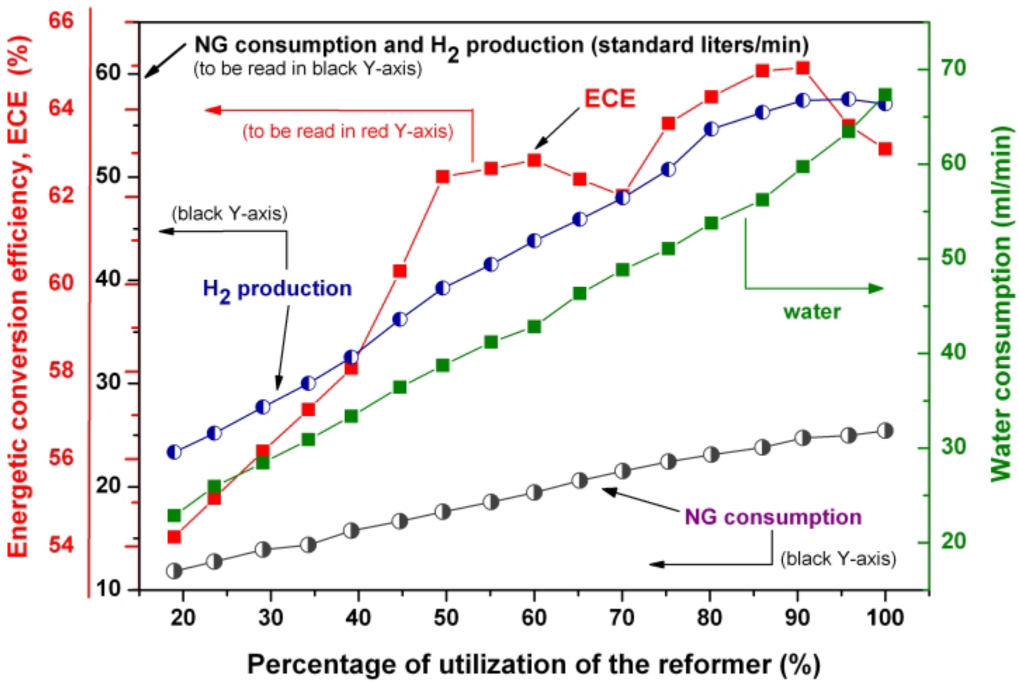

Figure 2. Characteristic curves of the NG reformer: flow rates of consumption of NG and deionized water, hydrogen production flow rate, and average energetic conversion efficiency (read in red y-axis) in function of the percentage of utilization of the reformer.

Although the relationship between the flows is considered, as expected, almost linear, it is noted that near the full capacity of the reformer (nominal hydrogen production flow rate) there is a deviation from the trend, showing a decrease in its efficiency, which, throughout the range, ranged from 54.2 to 64.2%, reaching in the tests, a maximum of 64.9% between 80 and 90% of the nominal capacity, range in which occurs a larger increase in water consumption. Peak production of hydrogen by NG reforming was 61.6 l/min corresponding to a consumption of 26.4 l/min of NG, as shown in Figure 2. Additionally, Table 1 shows the results obtained by chemical analysis by gas chromatography of the reformer effluent (H_2-rich gas), which show that, under the conditions evaluated, the hydrogen produced in FPM60-NG showed excellent level of purity, being very appropriate for use in a PEMFC. Based on these results it is noted that there is a small improvement of the indicators when the reformer is operating at steady state.

Table 1. Results from gas chromatography of the effluent of the FPM60-NG reformer (concentrations in ppm).

Analyzed Impurities	At start-up condition (1)	At steady state condition (2)	Operating in low production (3)
CO	1.0 ± 0.5	ND	ND
CO_2	2.5 ± 0.8	1.0 ± 0.8	1.0 ± 0.8
CH_4	20 ± 4	8 ± 4	15 ± 4
C_2H_6	3 ± 1	ND	ND
H_2S	ND	ND	ND

(1) : Percentage of utilization of the reformer = 50% (first effluent). ND = Not detected.
(2) : Percentage of utilization of the reformer = 80% (after 2h of operation).
(3) : Percentage of utilization of the reformer = 30% (after 10min of operation).

Figure 3 shows the average curves that relate the fuel cell voltage (potential, U) and the electric generated power (P) to the electrical current (I), generated by coupled charge, for the PEMFC-5kWe evaluated unit in good electrocatalytic activation conditions. In addition, Figure 4 shows the experimental I x U and I x P curves in the typical region of operation (intermediate region of the Figure 3) of the 5kWe PEMFC and two theoretical curves for the thermal power (P_T) available - one is only referring to heat waste of the fuel cell and another related to heat recovery in whole system (global thermal power, including the heat waste of the NG reformer) - assuming losses of around 25% in their respective thermal transfer systems, mainly because of the low thermodynamic quality heat waste of the case under consideration (PEMFC are low temperature fuel cells) (Furtado *et al.*, 2009).

The curve I x U shown in Figure 3 shows the three typical regions of operation of a fuel cell. The region up to 20 A, which it is dominated by activation losses, presents, in this case, greater instability and variability of the fuel cell voltage, probably due to the non-uniformity of behavior between 90 PEM single fuel cells in initial operational conditions (below 30% of nominal power). In the end of the intermediate region of electrical current, between 20 and 90 A, where the voltage fall is mainly due to the ohmic resistance, the fuel cell power reaches the maximum value, suggesting that in this case the humidification conditions are quite adequate and that the initial heterogeneity of behavior of the different single PEM fuel cells was replaced, probably due to hydrothermal equilibrium of the system. However, the level of corresponding potential, deer of 55 V or 0.61 V per single fuel cell is, possibly, even a little low to sustain operation in steady state for long periods of time. The optimization of the operating conditions may further enhance this potential. In fact, the values of potential per single fuel cell of about 0.60-0.70 V are more feasible for commercial applications (therefore, in good conditions for activation) (Radulescu *et al.*, 2008). For currents above 90 A the concentration polarization (diffusional) is predominant and power and potential curves have sharp fall in the high current region. Thus, the operation in this region can damage the fuel cells due to the electrothermal collapse of the membrane electrolyte, due to formation of hot spots in the polymer membrane surface (Ramaswamy *et al.*, 2008).

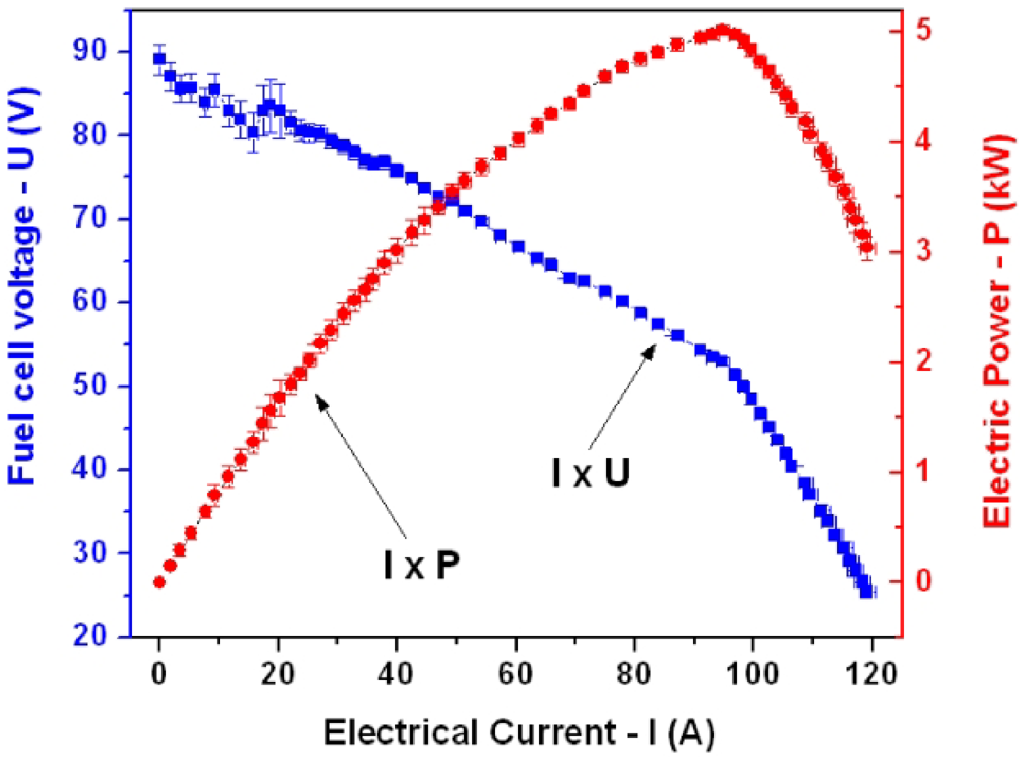

Figure 3. Performance curves (I x U e I x P) of the 5kWe PEMFC-Natural gas reformer power cogeneration system.

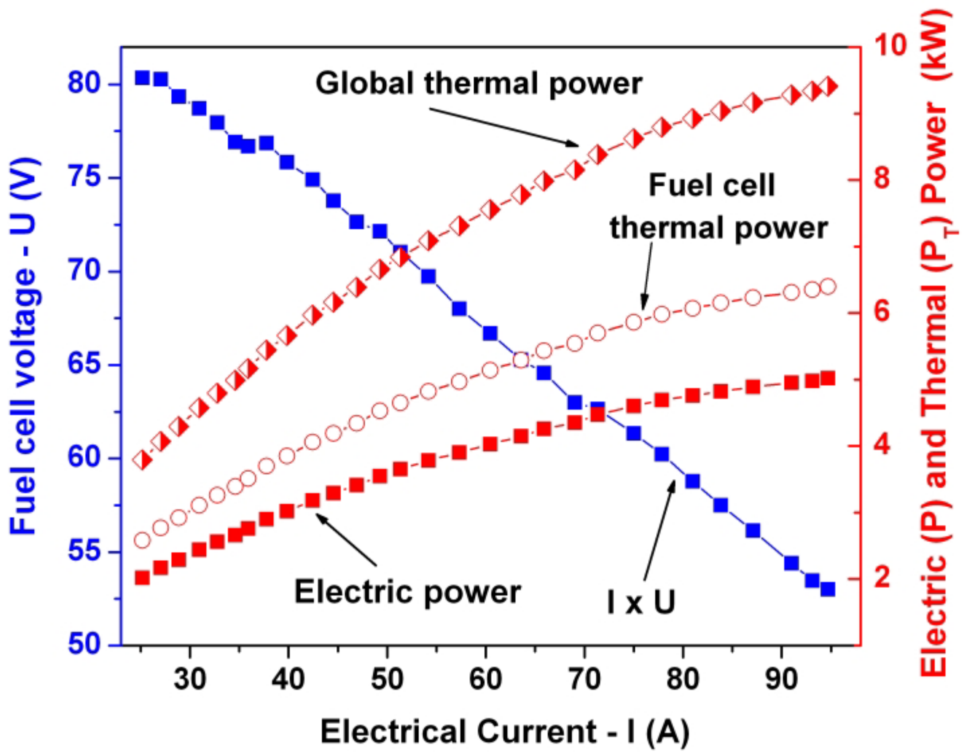

Figure 4. Characteristic curve I x U, electric and thermal power versus electrical current in the typical region of operation (intermediate region of the Figure 3) of the analyzed 5kWe PEMFC-Natural gas reformer power cogeneration system.

In order to complement the above analysis it appears in Figure 5 the behavior of the fuel cell potential per single fuel cell and the ratio between fuel cell voltage and open circuit voltage (OCV) in function of the increasing of the power supplied by fuel cell. As in good activation conditions the total OCV is 89.1 V (sum of the OCV in 90 single fuel cells) the considered two curves are practically coincided, showing that in the whole operation profile the average potential per single fuel cell is more than 0.60 V.

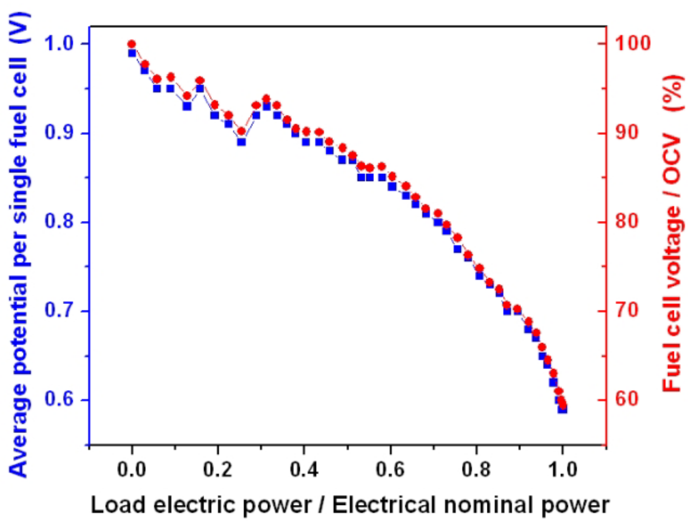

Figure 5. Curves of average potential per single fuel cell and the ratio between fuel cell voltage and OCV in function of the electric power used..

In fact, the influence of the activation conditions of the fuel cell electrocatalytic system on the performance of the generation system is of great importance, as can be seen in Figure 6, in which there is clearly the process of activation of the 5kWe PEMFC analyzed, since the four curves (numbered 1 to 4, in increasing order of activation) show, for the same applied current, potential (fuel cell voltage levels) increased. For example, to a current of 60 A, taken as a characteristic point of the region of operation, the difference in potential between the curves 1 and 4 is 31.4% (16 V), which represents a loss of power of the order of 1 kW, 20% of the nominal electric power of the fuel cell. Moreover, the OCVs associated with 1 to 4 curves (respectively, 81.73, 85.12, 87.73 and 90.4 V, it means a relative difference of 9.6% between the curves 1 and 4), also shows the activation process of the fuel cell. In Figure 6, in the right y-axis, it has been on the relative percentual variation of each pair of curves (1 and 2, 2 and 3, 3 and 4), showing that, as the curves 2 and 3 are close, the relative variation of potential between them is small. The opposite behavior is verified between 1 and 2 curves, and between curves 3 and 4. Additionally, Figure 7 shows that the time-dependent relative percentual variation (voltage percentage/second) is relatively high at the beginning of the operation, but becomes almost constant after 200 second of operation (or in regions of medium and high currents).

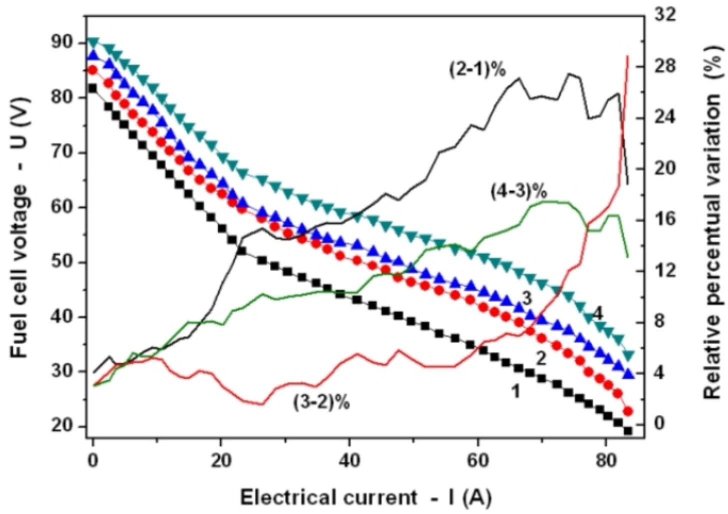

Figure 6. Results of electrochemical activation process tests of the 5kWe-PEMFC: four curves I x U numbered (1 to 4) in increasing order of activation, and respectives relative percentual variations between each pair of curves.

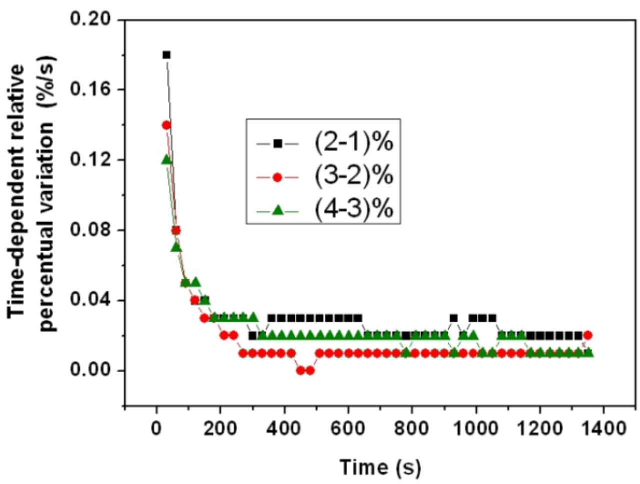

Figure 7. Results of electrochemical activation process tests of the 5kWe-PEMFC: relative percentual variations (in relation to the curves shown in Figure 6) in function of the tested operation time.

In turn, the activation behavior of the fuel cell influence the efficiency of the generation system, as seen in Figure 8, that shows the efficiencies of the 5kWe PEMFC, of the NG reformer and of the global system in function of the increasing of the power supplied by fuel cell in electrical generation mode.

As noted by Barbir (2005), the fuel cell efficiency at partial load can sometimes be slightly higher than that of the system operating in nominal power, mainly due to the efficiency of the PEMFC in greater loads (high power) minors, as it is operating at higher potential. Two other secondary factors that contribute to reducing the efficiency of the system operating at full load are the high thermal losses in the reform (which, in general, works with high air flow) and the sum of the parasites powers associated with auxiliary equipment and subsystems of the generation system, which, at a maximum load, also represent major losses.

Still considering Figure 8, it is interesting to note that the global efficiency curve for the system under study is quite similar to that of the 3 kWe residential generate system, also based on a PEMFC, studied by Barbir *et al.* (2000). In both cases, from approximately 30% of nominal power to change the efficiency due to the increase of the load is much lower in relation to that characteristic of the initial third of the range power. Moreover, below 30% of nominal power, it follows the observation that is not productive generation operating systems for this type of situation in very small part load (high idle capacity) (Hubert *et al.*, 2006). Besides this fact, it is precisely in this power range (where the polarization of activation is predominant) that was observed the largest PEMFC potential variability in the function of electrical current demanded, as was evidenced in the I x U curve shown in Figure 3. However, in the case of cogeneration system, the overall efficiency can be increased considerably, since much of the heat energy available can be used. Moreover, the efficiency of the NG reformer presents more variability from the 2.5kWe (50% of nominal system power).

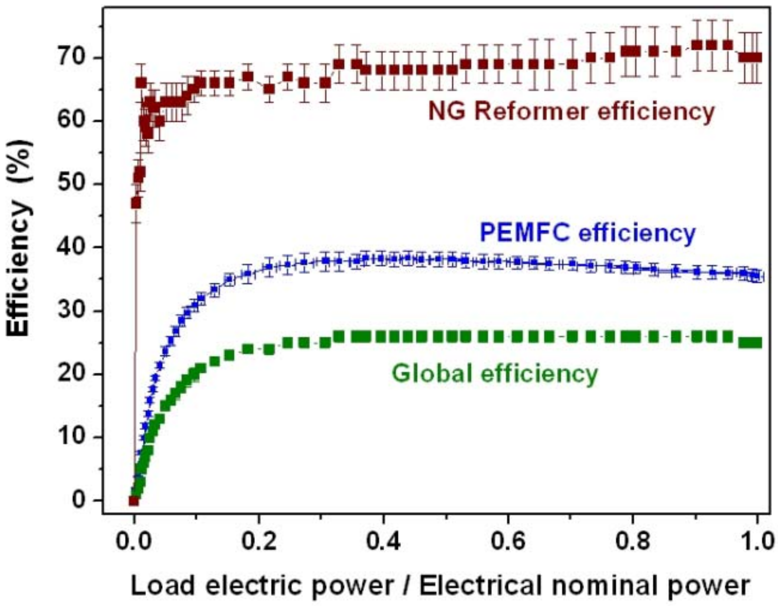

Figure 8. Relationships between efficiencies and electric power used.

About the impacts of the greater global efficiency of cogeneration system, in fact, Figures 9 and 10 shows the main results of the technical-economic analysis associated to energy performance results on cogeneration fuel cell-based system studied in this work. In Figure 9 are presented the cost results obtained by simulation associated with the generation of electricity in cases of pure electrical generation and cogeneration (combined heat and power, CHP) modes with basis in the energetic performance shown in Figure 4. The economic analysis results – in terms of fixed investment, operation and maintenance costs (O&M), primary fuel costs (in the case, natural gas) and cost of the electrical energy generated (CoE) - operating the system according to the profiles presented in Figure 4, in situations of pure electrical generation and two cogeneration (CHP) modes (waste heat recovery only in the PEMFC-5kWe and, alternatively, in both equipments, fuel cell unit and NG reformer). The results indicate reductions of around 9.7% and 20.7% in the CoE, respectively for the two cases of cogeneration, in relation to case of only electrical generation, according to the best energetic use of the primary fuel. In fact, the CoE (in US$/MWh) falls to 178 (electric generation only) to 160 (co-generation in the fuel cell) and 140 (global cogeneration), while that their fixed investments (in US$/MWh) presented much less significant increases (68.2, 70.3 and 73.7 respectively). But the relative cost of the fuel (NG) falls of 96.0 US$/MWh (electric generation only) to 75.8 (in cogeneration mode only in fuel cell) and 51.4 (global cogeneration).

More details about the methods for heat recovery of the considered system can be seen in the work of Siqueira *et al.* (2006), which considers the engineering requirements and conceptual designs associated with different possibilities and configurations of equipment (which will be responsible for small increases in fixed investment in CHP modes). Indeed, the recovery of the thermal waste in the PEMFC-5kWe and in the NG Reformer can be achieved by mixing up the respectives heat flows (which results in less investment, but with less efficiency of recovery) or separately (representing more investment, but with maximum heat energy recovery). In the present work it was adopted this second alternative.

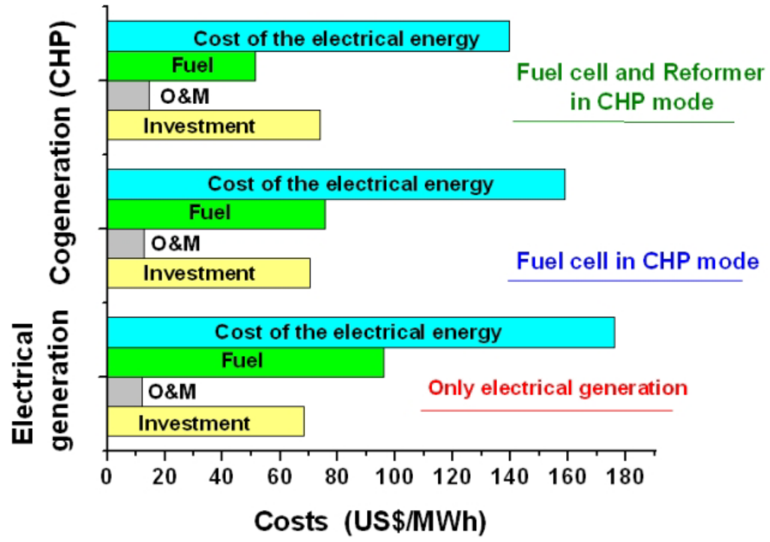

Figure 9. Cost results associated with the generation of electricity in cases of pure electrical generation and cogeneration modes.

Additionally, Figure 10 shows the results of a sensitivity analysis (see Table 2 for a full specification of the base case) about the influences of the overall electrical efficiency, of the fixed investment and of the NG cost on the CoE of the global cogeneration system (PEMFC and reformer), showing the significantly higher sensitivity of the CoE in relation to the system efficiency, which will increase significantly reducing the CoE.

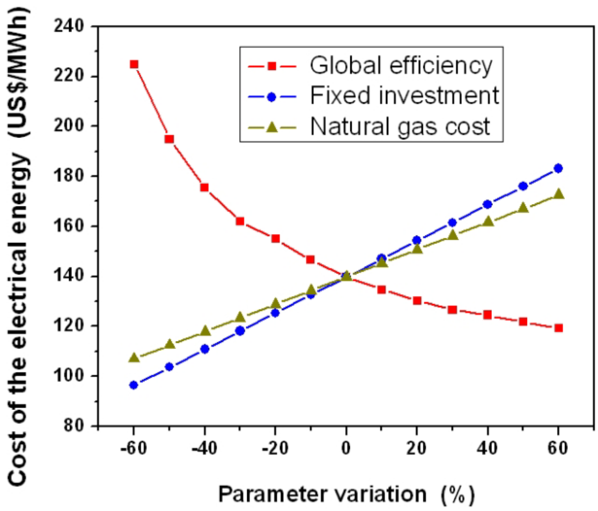

Figure 10. Results of a monoparametric sensibility analysis about the influences of the global efficiency, fixed investment and natural gas cost on the cost of the electrical energy generated by the cogeneration system.

Table 2. Specification of the base case on the sensibility analysis presented in Figure 10.

Parameter	**Value**
Nominal electric power	5 kW
Useful thermal power	6.4 kW
Natural gas consumption	28 l/min
Natural gas cost	US$ 15.00/GJ
Global electrical efficiency	28%
Fixed investment	US$ 3,000/kW
Interest rate	15% annual
Capacity factor	1.0
Project time	5 years

In fact, we can consider that the continuous improvement of the fuel cell technology, resulting in increasing of the efficiency and concurrently reducing of their acquisition and installation costs, in a scenario where an energy and environmentally technology will be the object of political government to encourage its adoption, would provide conditions for the CoE becomes even more attractive. Furthermore, the use and consequent accounting of the waste heat, supplying heating or cooling facilities energy, means to increase efficiency of use of fuel. Accordingly, as seen in the work of Colella (2002) for some fuel cell applications, the electrical generation efficiency is not the main parameter to be optimized, but the combination of electrical and thermal efficiencies and the fuel cell voltage operation. This observation is consistent with the results and analysis developed in the works of Lasher *et al*. (2006) e de Staffell *et al*. (2008), which identified market niches for PEMFC applications, and emphasized the implementation of CHP systems.

Even in this respect, Gigliucci *et al.* (2004) also evaluated a CHP system consisting of a PEMFC-4kWe and of a natural gas fuel processor, found similar I x U behavior, also showing the nominal power at 90-100 A, but with slightly lower values of efficiencies than those reported in this work, probably due to the greater energetic integration of the system analyzed here.

4. CONCLUSIONS

The results indicate that the fuel cell-based power generation system can operate with potential per single fuel cell of the order of 0.60 V or higher throughout the power range of the system and the efficiency of the generation system is almost stable for electric power to more than 1.5 kW, with electrical efficiency peak of 38%. Additionally, it was estimated the main parameters that characterize the economic operation of the system considered in situations of cogeneration and pure electrical generation, indicating that there is a reduction of around 20% in the cost of the electricity generated in the first case for the second. Furthermore, we presented the curves of hydrogen production and natural gas and water consumptions in the natural gas reformer used in the power generation system evaluated, which presented the highest rate of production of hydrogen equal to 61.6 l/min corresponding to a consumption of 26.4 l/min of natural gas, showing that the maximum efficiency of this equipment is obtained in high flow rates, between 80 and 90% of the nominal hydrogen production flow rate.

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