Proceedings of ENCIT 2010
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13th Brazilian Congress of Thermal Sciences and Engineering
December 05-10, 2010, Uberlandia, MG, Brazil

# SELF-ENERGY PRODUCTION APPLIED TO BUILDINGS

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***Abstract.*** *The decentralization of energy production in order to obtain better environmental conditions, reducing greenhouse gas emissions and the cost reduction of electricity and thermal energy consumed in residential buildings has been proposed in the literature. This paper proposes to demonstrate what are the chances of having a micro-cogeneration system toward the residential application. In this study, we contemplate the technologies involved and their possible inputs that are arranged in a superstructure to be studied. As a first step we obtain the cost of the products generated by the configuration that consists basically of two sources of power generation, and through optimization calculations intended to obtain the best configuration, taking into consideration the selection between four fuels, two equipment generators (Fuel Cell and Internal Combustion Engine)and three levels of energy production for each one. An economic analysis is also presented to evaluate the opportunity of selling the energy generated considering the fluctuations of the residential building consumption needs.*

***Keywords****: cogeneration, micro generation, fuel cell, internal combustion engine, residential self-generation, optimal operation*

## 1. INTRODUCTION

Cogeneration systems will contribute to expansion of install capacity, decongestion and increased transmition system reliability, diversifying energy sources and expanding business opportunities for private capital in the Brazilian market. Brazil has significant implantation potential for small cogeneration plants, especially in the tertiary sector, which concentrates a large number of small businesses that need electricity, steam, hot water and / or chilled water for cooling.

In this scenario, it becomes feasible to use new technologies (clean technologies), renewable energy without $CO_2$ emission, or natural gas / biogas in micro-generation, with higher efficiency in terms of emissions. Although no longer be a totally new idea, micro-generation has found a way favorable to revolution based on clean technology. The stimulus comes from the battle against climate change, rising oil prices, the need for reliable energy supply and technological progress itself.

Based on a micro cogeneration power configuration directed to residential condominiums, it is intended to select equipment by using optimization analysis to define the technology and respective capacity that best fits a heat and power demand, intending to obtain the maximum recipe and better utilization of energy for the condominium.

To do this, set up a cogeneration power configuration in which it offers the possibility to operate with an internal combustion engine or a fuel cell, the cogeneration system have to supply electricity and hot water to a residential condominium that consists of 30 apartments, whit three persons per apartment in average.

For this configuration, we determined the range of power that must be installed, considering three levels with three different outfits, and there may be able to purchase electric power to supplement the missing energy, or the sale of surplus electricity to the electric concessionaire.

The optimization analysis is proposed to also allow the decision-making on the fuel used in settings such as ethanol, diesel, hydrogen and natural gas.

The proposal to provide a configuration with an internal combustion engine and a configuration with the fuel cell is mainly by ecological and economic issues, thus allowing to assess the feasibility of installing a new technology with a configuration already established in the market for micro CHP energy.

## 2. MICRO COGENERATION APPLYING BY RESIDENTIAL BUILDINGS

Accadia et al. (2003), in a recent paper, analyzed energy micro-generation growing for the production of thermal and electrical energy for residential and commercial use considering the various options available in the market for that purpose. For these authors, there are basically three schemes available in the market, primarily devoted to the internal combustion engine, followed by fuel cells and finally a system that still follows on a trial basis, the Stirling engine.

A configuration was tested in a residence using a micro-system based on an internal combustion engine. To simulate the consumption of a residence, it was installed some household equipment and some fan coils, determining power consumption and heat in this way. The electricity demand was recorded at 10 kW while the thermal demand stands at 30 kW. Fig. 1 illustrates the structure proposed for data collection.

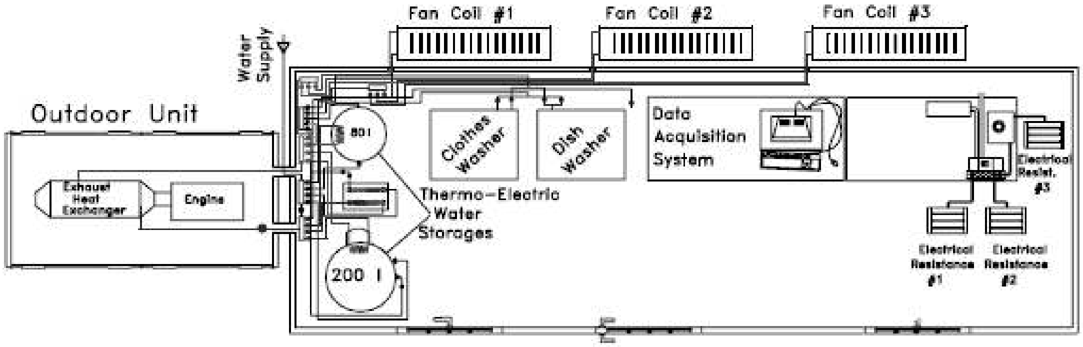

Figure 1 – Test Model Layout

The study by Dorer et al. (2005) focuses on considering the pollution generated in conventional cogeneration systems; this paper presents a configuration with fuel cells operating in a cogeneration system in two types of residential buildings. The main motivation of authors to conduct this study was the high efficiency in producing electricity through fuel cells combined with low emission of polluting gases and low noise working. The model is governed by the flow chart shown by Fig. 2.

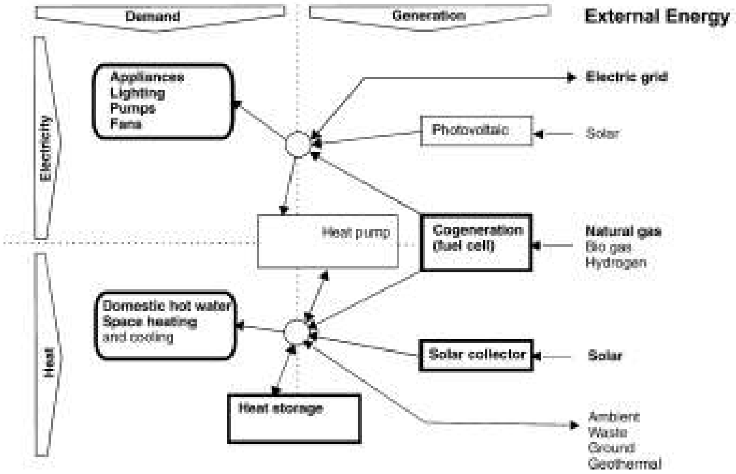

Figure 2 – Energy electricity and heat demands managing in residential system.

For this study, two types of residential buildings were established, single and multi residential buildings, thus separating the levels of demand for hot water and electricity. Water consumption and electricity in both configurations composed a graph of consumption over a week. With the demand data, three types of equipment, two fuel cells and with a boiler, were considered. The authors concluded that fuel cells, when compared with the boiler configuration, both using natural gas, have an advantage up to 48% with respect to the use of burning fuel, besides being less polluting.

The paper presented by Onovwiona (2006) demonstrates a technical-economic model using internal combustion engine, generating heat and electricity for a residential installation. Using a topping model, i.e., prioritizing the production of electricity, the configuration shown in fig.3 was proposed for attending the residential demands. This research was motivated by the interest augmentation for the cogeneration market for residential application, since cogeneration systems have the ability to produce electricity and heat using the same system, with better use of fuel which is now used only in boiler efficiency of 30%. With the cogeneration system, 80% utilization of spent fuel can be obtained.

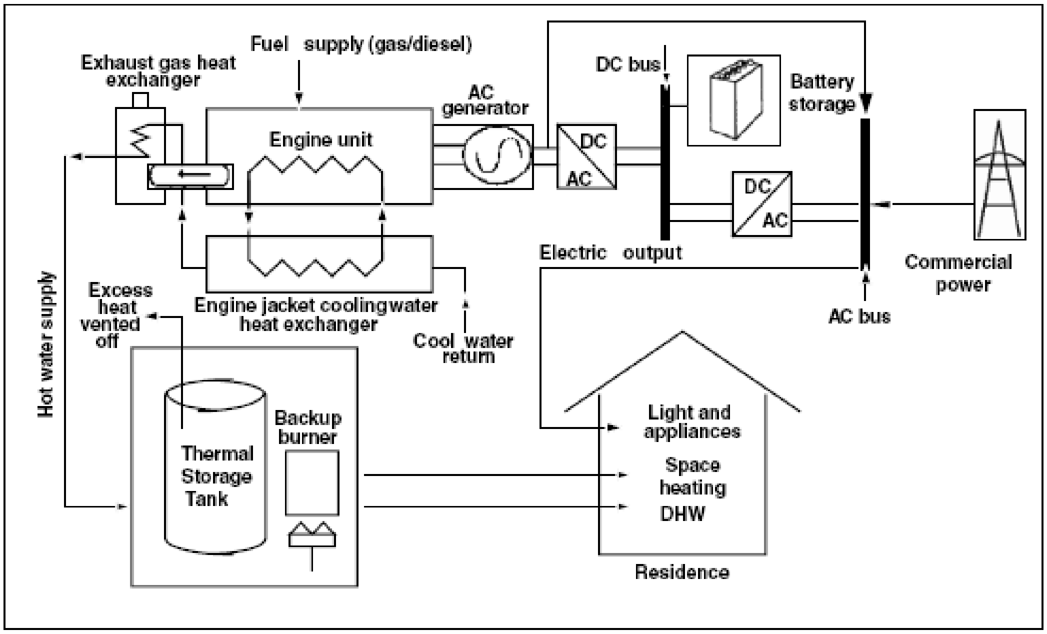

Figure 3 – Cogeneration model system using internal combustion engine with thermal energy storage tank.

The differential system proposed by Dorer and et al. (2005) is the storage of electrical energy and heat, allowing to switch to energy, not needing to be connected with the equipment at all times. The focus of the paper was to select an appropriate setting considering the capacity of engines and correctly size of tanks as their capacity for the cogeneration system optimally functioning.

For this, the authors performed a study of fluctuations in energy consumption considering the consumption of hot water and electricity throughout the year, demonstrating the effects of seasonality and more specifically over the 24 hours a day. Whit these consumption data, the authors proposed three different levels of production, using three different engines, one generating 6 kW of power, another 3.5 kW and finally another with 2 kW. With these settings there is the possibility to demonstrate three basic scenarios, the first with the possibility of selling electric power utility, the other producing only for self-sufficiency and the latter buying power of the concessionaire at some times of peak consumption. Figures 4 and 5 illustrate the results of analysis carried out in time basis.

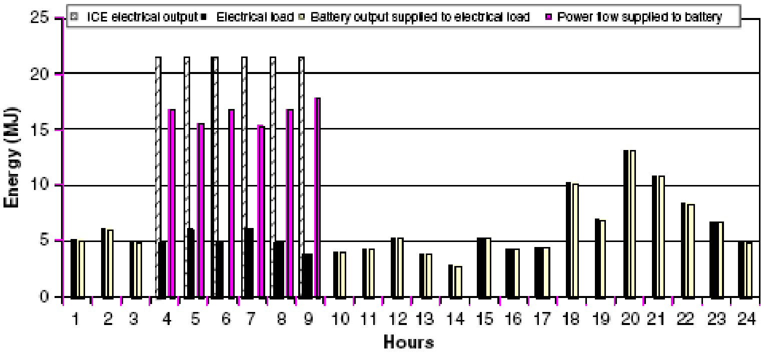

Figure. 4 – Electric energy consumption fluctuation.

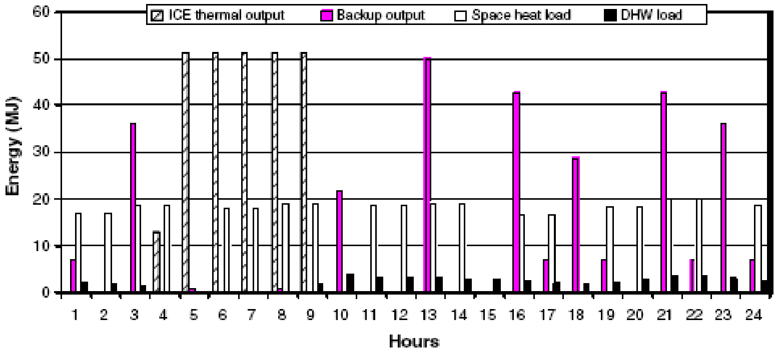

Figure 5 – Hot water consumption fluctuation.

Based on this brief review of the literature, it is noticed that there are studies in this growing field of knowledge and a drive up to the providers of micro-systems in the world, mainly in Asia and Europe, which is actually a positive influence on the Brazilian market. The issue of decentralization of energy production is nowadays being more appealing, especially due to the environmental question, the development of new technologies, the cost/ benefit attractiveness.

### 2.1. Proposed structure

The proposed superstructure was composed for attending the energy needs of a residential condominium of 30 families, with 3 persons per apartment on average. The energetic demand was based on inferences taking into account average energy consumption without seasonal variations and fluctuations throughout the day. A hot water tank and a reservoir of electrical energy (batteries) were considered for future analysis considering these time-series variations. The tank has specific 2000 L capacity and operates at a temperature between 60-90 º C.

It was considered an average per capita consumption of 85 kWh monthly, which refers to a middle class apartment with full electric electronic equipment. There is therefore a need for electricity consumption to be supplied by a number or configuration that generates approximately 10 kW of electric power.

In the case of a micro cogeneration system, there is also the generation of hot water to be consumed by these families. It is estimated that the average per capita consumption of hot water is of 20 L per day.

As was also established in this study, the configuration may generates enough power for the whole neighborhood, but also the condominium can buy electricity when there is a lack of it or even sell the electricity to the utility when there is a surplus. It will not be considered hot water selling (as in a district heating system) given the difficulties of heat transfer and the need for investment in distribution networks, not usual for Brazilian conditions.

For composing the proposed superstructure it was taken into account the acquisition of equipment available in the market, not limited by meteorological conditions and highly reliable, and in this way the internal combustion engine was chose. However, the noise and environmental pollution are disadvantages that must be in mind in the decision-making process; so, this technology was confronted with fuel cell technology, a less pollutant and low noise system. Technical data of these two technologies were obtained from manufacturer data sheets and costs involved in acquisition and maintenance/operation were obtained. Three equipment of each technology were considered to accomplish the analysis to define the most advantageous in financial terms, considering selling and buying power, self-sufficiency and/or selling of excess energy. Table 1 presents the technical data sheet of such equipment; the technologies were divided considering the fuels – natural gas and diesel oil for combustion engine and ethanol and hydrogen for fuel cells.

The software Lingo 9.0 was chosen to evaluate the optimization problem that consists in defining the configuration that is more economically advantageous to be recommended to the condominium. As the configuration considered commercial equipment, calculations were made based on the input and output values available in the data sheets, without the possibility of developing intermediate thermodynamic results of the equipment involved this configuration. Figure 6 shows a flow diagram of the configuration.

Table 1 – Technical data sheet of equipment.

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MCI selection - Natural Gas** | | | | | | | | | | | | | | |
| Model | Manufacturer | Out Put (kW) | Gas consumition (kW) | Gas Flow (kg/s) | Heat Recovery volume (kW) | Hot Water temperture © | Hot water Flow Volume (L/seg) | Reservoir capacity (L) | reservoir temperture | Overall efficiency (%) | Power generation efficiency (%) | Heat Recovery (%) | Valor (US$) | Disponivel em : |
| CP5VB - SN (P) J | Yanmar | 5 | 17.2 | 0.000335702 | 9,6 | 60 a 65 | 0.46 | 120 | 30 a 50 | 85 | 29 | 56 | 3500 | www.yanmar.co.jp/en/energy/cogeneration/5kw.html |
| CP10VB1 | Yanmar | 9.9 | 31.4 | 0.000612852 | 16,8 | 60 a 65 | 0.803333333 | 120 | 30 a 55 | 85 | 31,5 | 53,5 | 5153 | www.yanmar.co.jp/en/energy/cogeneration/9.9kw.html |
| CP25VB2 | Yanmar | 25 | 74.6 | 0.00145601 | 38,4 | 60 a 65 | 1.833333333 | 120 | | 85 | 33,5 | 51,5 | 6500 | www.yanmar.co.jp/en/energy/cogeneration/25kw.html |
| **MCI selection - Diesel** | | | | | | | | | | | | | | |
| Model | Manufacturer | Out Put (kW) | Comb consumition (kW) | Combustion Flow (kg/s) | Heat Recovery volume (kW) MJ/h | Hot Water temperture © | Hot water Flow Volume (L/seg) | Reservoir capacity (L) | reservoir temperture | Overall efficiency (%) | Power generation efficiency (%) | Heat Recovery (%) | Valor | Disponivel em : |
| GL 7000 | Kubota | 7 | 26.06449444 | 0.000613889 | 9.66 | 60 a 70 | 0.46 | 120 | 30 a 50 | 0.639184 | 0.2685646 | 0.37061912 | 3500 | www.kubotaengine.com |
| GL 11000 | Kubota | 11 | 41.10170278 | 0.000968056 | 17.2 | 60 a 70 | 0.82 | 120 | 30 a 50 | 0.686103 | 0.2676288 | 0.418474147 | 5153 | www.kubotaengine.com |
| SQ - 33 | Kubota | 25.2 | 90.22325 | 0.002125 | 42.1 | 60 a 70 | 2.017 | 120 | 30 a 50 | 0.745927 | 0.2793072 | 0.4666203 | 6500 | www.kubotaengine.com |
| **FC selection- Ethanol** | | | | | | | | | | | | | | |
| Model | Manufacturer | Out Put (kW) | Comb consumition (kW) | Combustion Flow (kg/s) | Heat Recovery volume (kW) MJ/h | Hot Water temperture © | Hot water Flow Volume (L/seg) | Reservoir capacity (L) | reservoir temperture | Overall efficiency (%) | Power generation efficiency (%) | Heat Recovery (%) | Valor | Disponivel em : |
| EFOY PRO series | SFC | 5.5 | 14.86 | 0.000525815 | 7.8758 | 60 a 70 | 0.0393 | 120 | 30 a 50 | 0.9 | 0.37 | 0.53 | 6500 | http://pdf.directindustry.com/pdf/incat/fuel-cell-22825-56755-_2.html |
| EFOY PRO series | SFC | 11.1 | 30 | 0.001061537 | 15.9 | 60 a 70 | 0.0793 | 120 | 30 a 50 | 0.9 | 0.37 | 0.53 | 11115 | http://pdf.directindustry.com/pdf/incat/fuel-cell-22825-56856.html |
| EFOY PRO series | SFC | 31.1 | 84 | 0.002972304 | 44.52 | 60 a 70 | 0.22 | 120 | 30 a 50 | 0.9 | 0.37 | 0.53 | 19000 | http://pdf.directindustry.com/pdf/incat/fuel-cell-22825-131908-_2.html |
| **FC Selection - Hydrogen** | | | | | | | | | | | | | | |
| Model | Manufacturer | Out Put (W) | Gas consumition (kW) | Combustion Flow (kg/s) | Heat Recovery volume (kW) MJ/h | Hot Water temperture © | Hot water Flow Volume (L/seg) | Reservoir capacity (L) | reservoir temperture | Overall efficiency (%) | Power generation efficiency (%) | Heat Recovery (%) | Valor | Disponivel em : |
| HyPM XR4 | Hydrogenics | 4.5 | 8.18 | 6.81207E-05 | 2.863 | 60 a 70 | 0.032 | 120 | 30 a 50 | 0.9 | 0.55 | 0.35 | 6500 | http://pdf.directindustry.com/pdf/incat/fuel-cell-33492-75121-_5.html |
| HyPM XR8 | Hydrogenics | 8.5 | 15.45 | 0.000128663 | 5.4075 | 60 a 70 | 0.061 | 120 | 30 a 50 | 0.9 | 0.55 | 0.35 | 11115 | http://pdf.directindustry.com/pdf/incat/fuel-cell-22782-25251-_2.html |
| HyPM XR12 | Hydrogenics | 12.5 | 22.7 | 0.000189039 | 7.945 | 60 a 70 | 0.089 | 120 | 30 a 50 | 0.9 | 0.55 | 0.35 | 19000 | |

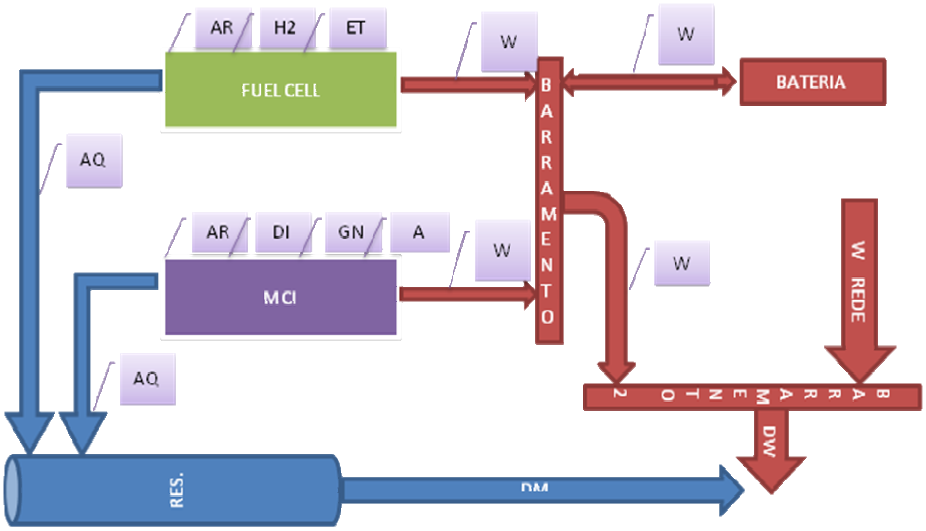

Figure 6. Diagram of superstructure propose

Table 2 presents the thermodynamic data for the configuration presented in Figure 6.

Table 2. thermodinamic data.

| | m (kg/s) | P (Mpa) | T (oC) | h (kJ/kg) | s (kJ/kgK) | EN (kW) | EX (kW) | EXQ (kW) | EXT (kW) |
|---|---|---|---|---|---|---|---|---|---|
| ARfc(gn) | 0.0008 | 0.1 | 25 | 104.6 | 0.37 | 0.0000 | 0.0000 | 0.434362 | 0.4344 |
| ARfc(gn) | 0.0015 | 0.1 | 25 | 104.6 | 0.37 | 0.0000 | 0.0000 | 0.820403 | 0.8204 |
| ARfc(gn) | 0.0023 | 0.1 | 25 | 104.6 | 0.37 | 0.0000 | 0.0001 | 1.205382 | 1.2054 |
| ARfc(et) | 0.0063 | 0.1 | 25 | 104.6 | 0.37 | 0.0000 | 0.0002 | 3.352786 | 3.3530 |
| ARfc(et) | 0.0127 | 0.1 | 25 | 104.6 | 0.37 | 0.0000 | 0.0004 | 6.768748 | 6.7691 |
| ARfc(et) | 0.0357 | 0.1 | 25 | 104.6 | 0.37 | 0.0000 | 0.0011 | 18.95249 | 18.9536 |
| H2fc | 0.0001 | | | | | 2.8630 | 2.8705 | 21.96279 | 24.8332 |
| H2fc | 0.0001 | | | | | 5.4075 | 5.4216 | 41.48229 | 46.9039 |
| H2fc | 0.0002 | | | | | 7.9450 | 7.9657 | 60.94809 | 68.9138 |
| ETfc | 0.0005 | | | | | 7.8758 | 7.9334 | 22.42206 | 30.3554 |
| ETfc | 0.0011 | | | | | 15.9000 | 16.0162 | 45.26661 | 61.2828 |
| ETfc | 0.0030 | | | | | 44.5200 | 44.8454 | 126.7465 | 171.5919 |
| Afc h2 | 0.0320 | 6 | 35 | 152 | 0.50 | 1.5168 | 0.2228 | 0 | 0.2228 |
| Afc h2 | 0.0610 | 6 | 35 | 152 | 0.50 | 2.8914 | 0.4246 | 0 | 0.4246 |
| Afc h2 | 0.0890 | 6 | 35 | 152 | 0.50 | 4.2186 | 0.6196 | 0 | 0.6196 |
| Afc et | 0.0393 | 6 | 35 | 152 | 0.50 | 1.8628 | 0.2736 | 0 | 0.2736 |
| Afc et | 0.0793 | 6 | 35 | 152 | 0.50 | 3.7588 | 0.5520 | 0 | 0.5520 |
| Afc et | 0.2200 | 6 | 35 | 152 | 0.50 | 10.4280 | 1.5315 | 0 | 1.5315 |
| Aqfc h2 | 0.0320 | | 80 | 335 | 1.08 | 7.3728 | 0.6251 | 0 | 0.6251 |
| Aqfc h3 | 0.0610 | | 80 | 335 | 1.08 | 14.0544 | 1.1916 | 0 | 1.1916 |
| Aqfc h4 | 0.0890 | | 80 | 335 | 1.08 | 20.5056 | 1.7386 | 0 | 1.7386 |
| Aqfc et | 0.0393 | | 80 | 335 | 1.08 | 9.0547 | 0.7677 | 0 | 0.7677 |
| Aqfc et | 0.0793 | | 80 | 335 | 1.08 | 18.2707 | 1.5491 | 0 | 1.5491 |
| Aqfc et | 0.2200 | | 80 | 335 | 1.08 | 50.6880 | 4.2977 | 0 | 4.2977 |
| Wfc | | | | | | 0.0000 | 0.0000 | 0 | 0.0000 |
| Wfc | | | | | | 0.0000 | 0.0000 | 0 | 0.0000 |
| Wfc | | | | | | 0.0000 | 0.0000 | 0 | 0.0000 |
| ARmc(gn) | 0.0047 | 0.1 | 25 | 104.6 | 0.37 | 0.0000 | 0.0001 | 2.497319 | 2.4975 |
| ARmc(gn) | 0.0086 | 0.1 | 25 | 104.6 | 0.37 | 0.0000 | 0.0003 | 4.559058 | 4.5593 |
| ARmc(gn) | 0.0204 | 0.1 | 25 | 104.6 | 0.37 | 0.0000 | 0.0006 | 10.83139 | 10.8320 |
| ARmc(D) | 0.0086 | 0.1 | 25 | 104.6 | 0.37 | 0.0000 | 0.0003 | 4.566775 | 4.5670 |
| ARmc(D) | 0.0136 | 0.1 | 25 | 104.6 | 0.37 | 0.0000 | 0.0004 | 7.201453 | 7.2019 |
| ARmc(D) | 0.0298 | 0.1 | 25 | 104.6 | 0.37 | 0.0000 | 0.0009 | 15.80807 | 15.8090 |
| GNmc | 0.0003 | | | | | 17.2000 | 17.2368 | 9.595783 | 26.8325 |
| GNmc | 0.0006 | | | | | 31.4000 | 31.4671 | 17.51788 | 48.9850 |
| GNmc | 0.0015 | | | | | 74.6000 | 74.7594 | 41.61892 | 116.3783 |
| Dmc | 0.0006 | | | | | 26.0645 | 26.1317 | 211.4711 | 237.6028 |
| Dmc | 0.0010 | | | | | 41.1017 | 41.2077 | 333.4736 | 374.6813 |
| Dmc | 0.0021 | | | | | 90.2233 | 90.4559 | 73.20152 | 163.6574 |
| Amc gn | 0.4600 | 6 | 35 | 152 | 0.50 | 21.8040 | 3.2022 | 0 | 3.2022 |
| Amc gn | 0.8033 | 6 | 35 | 152 | 0.50 | 38.0780 | 5.5923 | 0 | 5.5923 |
| Amc gn | 1.8333 | 6 | 35 | 152 | 0.50 | 86.9000 | 12.7626 | 0 | 12.7626 |
| Amc D | 0.4600 | 6 | 35 | 152 | 0.50 | 21.8040 | 3.2022 | 0 | 3.2022 |
| Amc D | 0.8200 | 6 | 35 | 152 | 0.50 | 38.8680 | 5.7083 | 0 | 5.7083 |
| Amc D | 2.0170 | 6 | 35 | 152 | 0.50 | 95.6058 | 14.0411 | 0 | 14.0411 |

## 2.2. Optimization modeling

The proposed mixed-integer linear modeling is presented. Exergy-based equations were formulated considering the exergy balance in the nodes. The equality method, which assumes that the unit exergy cost of the electromechanical portion is equivalent to the portion of heat that is extracted from it (Balestieri, 2002), was considered for the partition of costs.

The following set of equations was proposed to model the cogeneration scheme:

$$Caqm1*XPthm1+cdwm1*XPelm1 = Cgn*xgn1+Ca1*XPam1+Zmci1 \tag{1}$$

$$Caqm2*XPthm2+cdwm2*XPelm2 = Cgn*xgn2+Ca1*XPam2+Zmci2 \tag{2}$$

$$Caqm3*XPthm3+cdwm3*XPelm3 = Cgn*xgn3+Ca1*XPam3+Zmci3 \tag{3}$$

$$Caqm4*XPthm4+cdwm4*XPelm4 = Cdi*xdi4+Ca1*XPam4+Zmci4 \tag{4}$$

$$Caqm5*XPthm5+cdwm5*XPelm5 = Cdi*xdi5+Ca1*XPam5+Zmci5 \tag{5}$$

$$Caqm6*XPthm6+cdwm6*XPelm6 = Cdi*xdi6+Ca1*XPam6+Zmci6 \tag{6}$$

$$Caqf1*XPthf1+cdwf1*XPelf1 = Cet*xet1+Ca1*XPaf1+Zfc1 \tag{7}$$

$$Caqf2*XPthf2+cdwf2*XPelf2 = Cet*xet2+Ca1*XPaf2+Zfc2 \tag{8}$$

$$Caqf3*XPthf3+cdwf3*XPelf3 = Cet*xet3+Ca1*XPaf3+Zfc3 \tag{9}$$

$$Caqf4*XPthf4+cdwf4*XPelf4 = Ch2*xh24+Ca1*XPaf4+Zfc4 \tag{10}$$

$Caqf5*XPthf5+cdwf5*XPelf5 = Ch2*xh25+Ca1*XPaf5+Zfc5$ (11)
$Caqf6*XPthf6+cdwf6*XPelf6 = Ch2*xh26+Ca1*XPaf6+Zfc6$ (12)

**Método da Igualdade:**

*Cdwm1 (Engine 1 electric Power costs)= Caqm1(Engine 1 hot water costs)* (13)
*Cdwm2 (Engine 2 electric Power costs)= Caqm2(Engine 2 hot water costs)* (14)
*Cdwm3 (Engine 3 electric Power costs)= Caqm3(Engine 3 hot water costs)* (15)
*Cdwm4 (Engine 4 electric Power costs)= Caqm4(Engine 4 hot water costs)* (16)
*Cdwm5 (Engine 5 electric Power costs)= Caqm5(Engine 5 hot water costs)* (17)
*Cdwm6 (Engine 6 electric Power costs)= Caqm6(Engine 6 hot water costs)* (18)
*Cdwf1 (Fuel cell 1 electric Power costs)= Caqf1 (Fuel cell 1 hot water costs)* (19)
*Cdwf2 (Fuel cell 2 electric Power costs)= Caqf2 (Fuel cell 2 hot water costs)* (20)
*Cdwf3 (Fuel cell 3 electric Power costs)= Caqf3 (Fuel cell 3 hot water costs)* (21)
*Cdwf4 (Fuel cell 4 electric Power costs)= Caqf4 (Fuel cell 4 hot water costs)* (22)
*Cdwf5 (Fuel cell 5 electric Power costs)= Caqf5 (Fuel cell 5 hot water costs)* (23)
*Cdwf6 (Fuel cell 6 electric Power costs)= Caqf6 (Fuel cell 6 hot water costs)* (24)

The optimization problem can be formalized mathematically as follows:

**Objective function:**

$$min=Ymci1*(Zmci1+Cgn*Xgn1+Cmci+Cdwm1*XPelm1+Caqm1*XPthm1+Xpam1*Ca1)+Ymci2*(Zmci2+Cgn*Xgn2+Cmci+Cdwm2*XPelm2+Caqm2*XPthm2+Xpam2*Ca1)+Ymci3*(Zmci3+Cgn*Xgn3+Cmci+Cdwm3*XPelm3+Caqm3*XPthm3+Xpam3*Ca1)+Ymci4*(Zmci4+Cdi*Xdi4+Cmci+Cdwm4*XPelm4+Caqm4*XPthm4+Xpam4*Ca1)+Ymci5*(Zmci5+Cdi*Xdi5+Cmci+Cdwm5*XPelm5+Caqm5*XPthm5+Xpam5*Ca1)+Ymci6*(Zmci6+Cdi*Xdi6+Cmci+Cdwm6*XPelm6+Caqm6*XPthm6+Xpam6*Ca1)+Yfc1*(Zf1+Cet*Xet1+Cfc+Cdwf1*XPelf1+Caqf1*XPthf1)+Yfc2*(Zf2+Cet*Xet2+Cfc+Cdwf2*XPelf2+Caqf2*XPthf2)+Yfc3*(Zf3+Cet*Xet3+Cfc+Cdwf3*XPelf3+Caqf3*XPthf3)+Yfc4*(Zf4+Ch2*Xh24+Cfc+Cdwf4*XPelf4+Caqf4*XPthf4)+Yfc5*(Zf5+Ch2*Xh25+Cfc+Cdwf5*XPelf5+Caqf5*XPthf5)+Yfc6*(Zf6+Ch2*Xh26+Cfc+Cdwf6*XPelf6+Caqf6*XPthf6) \qquad (25)$$

**Data:**

Combustion costs in US$/kg:
*Cgn (Natural gás costs)= 0.1881* (26)
*Cet (Ethanol costs)= 0.7895* (27)
*Cdi (Diesel costs)= 0.5866* (28)
*Ch2 (Hydrogen costs)= 3.68* (29)

Maintenance costs in US$/kWh:
*Cmci (Engine manutention costs)= 0.015* (30)
*Cfc (Fuel cell manutention costs)= 0.05* (31)

Combustion flow in kg/h:
*Xgn1(Gas natural flow for engine 1)=1.08* (32)
*Xgn2(Gas natural flow for engine 2)=2.16* (33)
*Xgn3(Gas natural flow for engine 3)=5.4* (34)
*Xdi4(Diesel flow for engine 4) =2.16* (35)
*Xdi5(Diesel flow for engine 5) =3.6* (36)
*Xdi6(Diesel flow for engine 6) =7.56* (37)
*Xet1(Ethanol flow for fuel cell1 ) =1.8* (38)
*Xet2(Ethanol flow for fuel cell2 ) =3.96* (39)
*Xet3(Ethanol flow for fuel cell3 ) =10.8* (40)
*Xh24(Hydrogen flow for fuel cell4 ) =0.36* (41)
*Xh25(Ethanol flow for fuel cell5 ) =0.46* (42)
*Xh26(Ethanol flow for fuel cell6 ) =0.72* (43)

Electric power in kW:
*XPelm1(Engine 1 electric power)= 5* (44)
*XPelm2(Engine 2 electric power)= 9.9* (45)

*XPelm3(Engine 3 electric power)= 25* (46)
*XPelm4(Engine 4 electric power)= 7* (47)
*XPelm5(Engine 5 electric power)= 11* (48)
*XPelm6(Engine 6 electric power)= 25.2* (49)
*XPelf1(Fuel Cell 1 electric power)= 5.5* (50)
*XPelf2(Fuel Cell 2 electric power)= 11.1* (51)
*XPelf3(Fuel Cell 3 electric power)= 31.1* (52)
*XPelf4(Fuel Cell 4 electric power)= 7* (53)
*XPelf5(Fuel Cell 5 electric power)= 11* (54)
*XPelf6 (Fuel Cell 6 electric power)= 25.2* (55)

Exergy thermal power in kW*:*
*XPthm1 (Engine 1 exergy thermal power)= 9.6* (56)
*XPthm2 (Engine 2 exergy thermal power)= 16.8* (57)
*XPthm3 (Engine 3 exergy thermal power)= 38.4* (58)
*XPthm4 (Engine 4 exergy thermal power)= 9.66* (59)
*XPthm5 (Engine 5 exergy thermal power)= 17.2* (60)
*XPthm6 (Engine 6 exergy thermal power)= 42.1* (61)
*XPthf1 (Fuel cell 1 exergy thermal power)= 7.9* (62)
*XPthf2 (Fuel cell 2 exergy thermal power)= 15.9* (63)
*XPthf3 (Fuel cell 3 exergy thermal power)= 44.5* (64)
*XPthf4 (Fuel cell 4 exergy thermal power)= 2.9* (65)
*XPthf5 (Fuel cell 5 exergy thermal power)= 5.4* (66)
*XPthf6 (Fuel cell 6 exergy thermal power)= 7.9* (67)

Hot water flow in kg/h:
*Xaqm1 (Engine 1 hot water flow)= 1656* (68)
*Xaqm2 (Engine 2 hot water flow)= 2880* (69)
*Xaqm3 (Engine 3 hot water flow)= 6480* (70)
*Xaqm4 (Engine 4 hot water flow)= 1656* (71)
*Xaqm5 (Engine 5 hot water flow)= 2952* (72)
*Xaqm6 (Engine 6 hot water flow)= 7272* (73)
*Xaqf1 (Fuel cell 1 hot water flow)= 141.8* (74)
*Xaqf2 (Fuel cell 2 hot water flow)= 285.48* (75)
*Xaqf3 (Fuel cell 3 hot water flow)= 792* (76)
*Xaqf4 (Fuel cell 4 hot water flow)= 115.2* (77)
*Xaqf5 (Fuel cell 5 hot water flow)= 219.6* (78)
*Xaqf6 (Fuel cell 6 hot water flow)= 320.4* (79)

Water costs in US$/kWh:
*Ca1 (Water costs)= 0.291* (80)

Exergy water energy in kW:
*XPam1 (Engine 1 exergy water)= 3.2* (81)
*XPam2 (Engine 2 exergy water)= 5.59* (82)
*XPam3 (Engine 3 exergy water)= 12.8* (83)
*XPam4 (Engine 4 exergy water)= 3.2* (84)
*XPam5 (Engine 5 exergy water)= 5.7* (85)
*XPam6 (Engine 6 exergy water)= 14.1* (86)

Amortized investment in equipment, whereas the annual interest rate = 12.5% and time to be amortized over 10 years. Value expressed in US$/h:
*Zmci1 (Engine 1 costs investment) = 0.097* (87)
*Zmci2 (Engine 2 costs investment)= 0.14* (88)
*Zmci3 (Engine 3 costs investment)= 0.18* (89)
*Zmci4 (Engine 4 costs investment)= 0.10* (90)
*Zmci5 (Engine 5 costs investment)= 0.14* (91)
*Zmci6 (Engine 6 costs investment)= 0.18* (92)
*Zfc1 (Fuel cell 1 costs investment)= 0.18* (93)
*Zfc2 (Fuel cell 2 costs investment)= 0.31* (94)

$$Zfc3\ (\text{Fuel cell 3 costs investment}) = 0.53 \tag{95}$$
$$Zfc4\ (\text{Fuel cell 4 costs investment}) = 0.18 \tag{96}$$
$$Zfc5\ (\text{Fuel cell 5 costs investment}) = 0.31 \tag{97}$$
$$Zfc6\ (\text{Fuel cell 6 costs investment}) = 0.53 \tag{98}$$

**Restrições:**

$$\underbrace{Ymci1+Ymci2+Ymci3+Ymci4+Ymci5+Ymci6}_{\text{Engine}}+\underbrace{Yfc1+Yfc2+Yfc3+Yfc4+Yfc5+Yfc6}_{\text{Fuel Cell}}=1 \tag{99}$$

### 2.3. Results

Calculating the set of equations mentioned in item 2.2, you can get the values of exergy cost of the final products of all twelve cogeneration plants and through posted data as the operating cost and the cost of inputs is possible to know which of the 12 components reveals to be the most advantageous in terms of cost and efficiency. In Table 4 it is presented the selection of equipment that has the best cost/benefit and in Table 3 it is observed the cost of hot water and electricity generated for the selected technology.

The factors that led you to choose an engine 1 are directly related to the low investment cost ($ 3,500), one of the cheapest equipment, together with an overall exergy efficiency of around 85%. From these 85%, the thermal efficiency is of 56%.

Table 3 – Exergy products costs

| Equipamets | Electric energy US$/kW | Hot water US$/kW |
|---|---|---|
| Engine 1 | 0,084 | 0,084 |
| Engine 2 | 0,081 | 0,081 |
| Engine 3 | 0,077 | 0,077 |
| Engine 4 | 0,14 | 0,14 |
| Engine 5 | 0,14 | 0,14 |
| Engine 6 | 0,14 | 0,14 |
| Fuel cell 1 | 0,12 | 0,12 |
| Fuel cell 2 | 0,13 | 0,13 |
| Fuel cell 3 | 0,12 | 0,12 |
| Fuel cell 4 | 0,15 | 0,15 |
| Fuel cell 5 | 0,12 | 0,12 |
| Fuel cell 6 | 0,096 | 0,096 |

Table 4 – The final solution

| index | Model | Manufacturer | Out Put (kW) | Gas consumition (kW) | Gas Flow (kg/s) | Heat Recovery volume (kW) | Hot Water temperture © | Hot water Flow Volume (L/seg) | Reservoir capacity (L) | reservoir temperture | Overall efficiency (%) | Power generation efficiency (%) | Heat Recovery (%) | Valor (US$) | Disponivel em : |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | CP5VB - SN (P) J | Yanmar | 5 | 17.2 | 0.000335702 | 9,6 | 60 a 65 | 0.46 | 120 | 30 a 50 | 85 | 29 | 56 | 3500 | www.yanmar.co.jp/en/energy/cogeneration/5kw.html |

## 3. CONCLUSION

The internal combustion engine number 1 was selected through optimization calculations that took into account the investment cost and exergetic efficiencies of the equipment. These calculations do not take into account the rate of pollution and noise generated by the generating equipment.

Because it is a system whose energy generator is an internal combustion engine, very common in the domestic market, the costs of final products were very close to prices charged by electric utilities nationwide.

As a next step also worth mentioning the marketing of energy, such as considering the comparison of energy in the event of power failure and in case of sale or manufacture of surplus energy by following the fluctuations of consumption and seasonality.

The calculations show a tendency to become a viable fuel cell to replace the internal combustion engine, which shows the evolution of this equipment in the markets. The values of the final products generated by the same system of micro CHP but with a level of increased energy production, generated by the fuel cell shows values close to the selected, but still weight on the final assessment costs the investment cost, a negative point for fuel cells because it is a new technology and nowadays suffer with this question for a while, believed to be short, until its full development in terms of market penetration.

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## 5. SYMBOLS

Table 5 – Symbol list

| | | |
|---|---|---|
| C | Cost for combustion | US$/kg |
| C | Energy cost | US$/kWh |
| aqm | Hot water from the engine´s jacket | - |
| X | Flow | kg/h |
| XP | Power | kW |
| a | Water | - |
| gn | Natural Gas | - |
| di | Diesel | - |
| h2 | Hydrogen | - |
| et | Ethanol | - |
| mci | Internal combustion engine | - |
| Z | Investment | US$/h |
| fc | Fuel cell | - |
| el | Electric Energy | kW |
| th | Thermal Energy | kW |
| f | Fuel Cell | - |
| dw | Electric Power Output | kW |

## 6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.