Technical and Economic Study of Micro-cogeneration in Residential Scale: a Case Study

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Abstract. *This work presents the results from the research project, named "Desenvolvimento de Sistema Integrado de Aparelhos da Linha Branca Residencial Utilizando o Gás Natural como Agente Energético e Aglutinador – Ênfase no Sistema de Condicionamento de Ar pelo Processo de Absorção de Vapor com Queima de Gás Natural", sponsored by FINEP, PETROBRAS, COPERGÁS and UFPE. This project is based on the investigation of micro-cogeneration at residential scale, using natural gas as fuel source. After the Brazilian power crisis in 2000/2001, the use of natural gas has been incetived. The Ministry of Science and Technology (MCT) adopted the policy to increase the participation of the natural gas in the energetic matrix. In this light, this paper shows the financial analysis of a devised scenario where micro-cogeneration is employed. Two systems were proposed: one with a microturbine as primer mover and the other with an Internal Combustion Engine (ICE) as primer mover. Microturbines as primer movers still present higher specific capital costs. Internal Combustion Engines (ICE) fuelled with natural gas, could be a cost-effective alternative, but its major drawback is the low thermal efficiencies presented by such systems. All proposed systems generated positive cash flows, although some particularities should be observed to justify the investment. Microturbine has demonstrated to be the logical choice for stand-alone applications, where is not possible to sell exceeding power capacity. It also competes with ICE system when its specification capital cost is under USD 800/kWh or when the exchange rate is up to R$1.8/USD. For situations where it is possible to sell the exceeding power capacity, ICE systems prove to be a viable choice.*

Keywords. ***Cogeneration, Micropower, Microturbines, Absorption Chillers****, Heat Recovery Systems, Investment Analysis of Micro-cogeneration Systems, Sensitive Analysis of Micro-cogeneration System,* ***Thermal Storage.***

1. Introduction

Micro-cogeneration can have many purposes. It can be utilized for continuous use, for schedules of pick energy consumption, for emergency power generation systems, for power generation systems in remote areas, for generation of cold and heat and also for systems of energy that uses residues and biomass (U.S. DEPARTMENT OF ENERGY, 2000).

In a small scale, the micro-cogeneration has it application domain in the small private consumer as restaurants, hotels, block of houses, small factories, shopping centers, sport facilities, etc. An enormous sort of commercial applications can satisfy their electric power and thermal needs by using systems of micro-cogeneration. CEEETA (2002) CEEETA (2002) presented an study about the application of micro-cogeneration in Porytugal. Dentice D'Accadia et al. (2003) presented an experimental study about the application of micro-cogeneration for use in residential and commercial scale, with profile of electric demand up to 10 kW and demand of heat up to 30 kW.

Microgeneration is defined as power generation for capacities up to 200 kW. The use of microturbines as primer movers have became popular recently, but its specific capital cost is still high. Internal Combustion Engines (ICE) fuelled with natural gas, has demonstrated smaller specific capital costs. The major drawback of ICE based systems is low thermal efficiencies presented by such systems, which do not make them the better option for micro-cogeneration purposes. The smaller commercial microturbine available has a capacity of 30 kW for ISO conditions and internal combustion engines fuelled with natural gas, whose capacity ranges from 5 to 200 kW. For this work, the capacity of 30 kW will be adopted as reference electric capacity for the technical analysis of power generation.

The aim of this paper is to investigate the use of microgeneration, creating evaluation tools for analysing the technical and economic viability of such systems. These tools could be also utilised for similar power generation systems.

The present article seeks to share with the scientific community the experience of the Group of Thermal Engineering of UFPE in the area of cogeneration. This work represents a united effort between the Federal University of Pernambuco (UFPE), through his Group of Thermal Engineering (GET) and RedeGasEnergia (A Brazilian Joint in charge of promoting the use of natural gas) to accomplish research on micro-cogeneration using natural gas as primary energy source. The project is a part of a governmental strategy in which the Brazilian Government is motivating the rationalization of energy resources through several Governmental Programs at the same time that it is also looking for stimulating technological research and development, in order to improve the use of the natural gas. The project here described is named COGENCASA and is financed by PETROBRÁS and FINEP.

2. Project Characterisation

The thermal efficiency for the microturbine employed ion this system is 30% and for the internal combustion engine (ICE) is 35%. It represents that both equipment reject at least 70% of the fuel energy by heat transfer. For this reason, a cost-effective stand-alone off-grid installation of such systems, competing with utility companies, is improbable.

To increase the competitively of these systems, a better utilisation of the rejected heat is required. In this light, an absorption chiller with 10 TR capacity, a flue gas heat recovery system, and a thermal storage system could be installed. The thermal storage system could provide enough hot water to supply the daily requirements for typical residential applications, i.e. bathroom hot water. It is also possible to provide cool water for building refrigeration purposes.

To perform the technical and economic viability study, was developed software that generates the required data for this kind of analysis. The Thermal Engineering Group (GET) is also assembling a micro-cogeneration system in laboratory at Universidade Federal de Pernambuco (UFPE). The data generated with the software are obtained with the technical information and equipment performance curves provided by the vendors. These performances should be tested for local environmental conditions. The proposed systems (see Figure 1) will be installed at UFPE laboratories and this project is supported by a CTPETRO Programme, through a pool composed by FINEP, PETROBRAS, COPERGAS and UFPE. This test facility targets to complement the technical information provided by the vendors, to analyse the behaviour of such equipment for the local environmental conditions, serving as a valuable pilot plan for future utilisation of natural gas as fuel for power generation in micro scale.

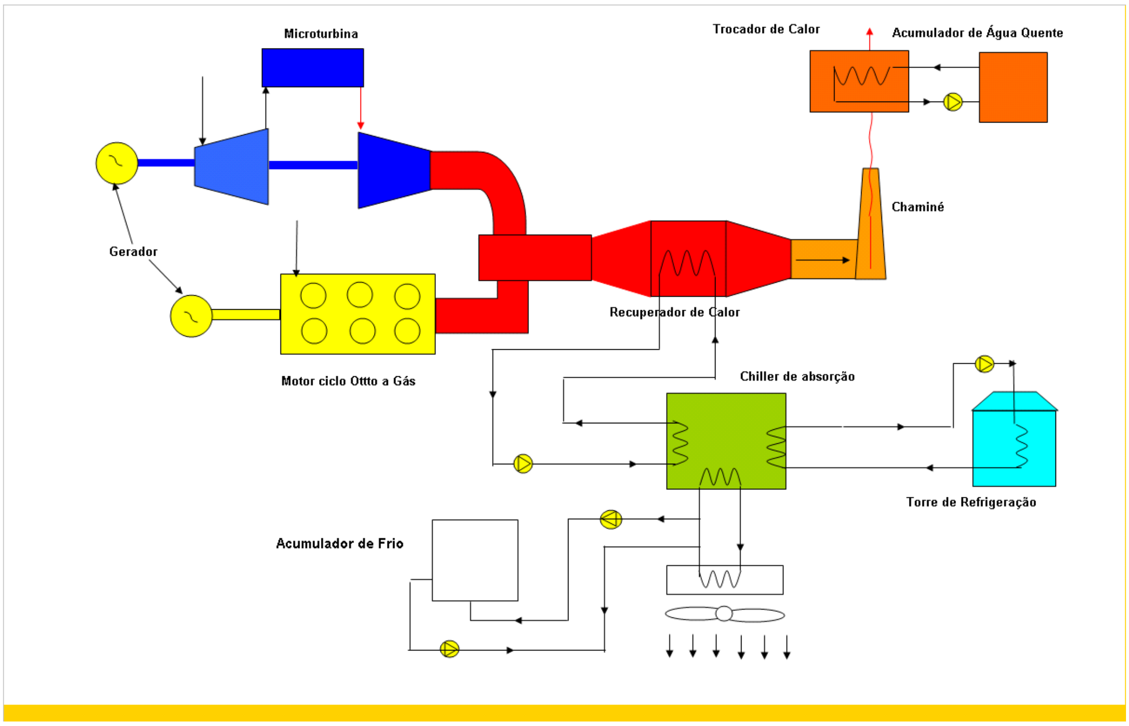

Figure 1 – Scheme of the microgeneration facility at UFPE.

3. System Description

The installed system is composed by a Capstone C30 HP microturbine with 30 kW capacity, one GM ICE fuelled by natural gas with 30 kW, one compact cross flow heat exchanger, one flue gas heat recovery system, one hot water fired absorption chiller with 10 TR capacity, a cooling tower and thermal storage systems for hot and cold water.

This equipment will be installed in a brand new facility at the Mechanical Engineering Department (DEMEC) of the UFPE, and the major objective is to serve as test rig for the simulation of the most variable operational conditions of a micro-cogeneration system. The characteristic data is presented in the Table 1 and were obtained from manufacturers catalogues at operational temperature of 32°C.

For a full operation regime, considering that both microturbine and internal combustion engine has the same capacity factor, the results are shown on Table C. The specific capital cost assumed for the sensitive analysis of each system is given by Table D, assuming a reference exchange rate of 3.5 R$/USD. Based on the data from Table D, the total capital cost for a system with a microturbine is USD 83 010 (R$ 290 535) and for a system with an internal combustion engine is USD 63 810 (R$ 223 335).

4. Numerical Simulation

The numerical simulation developed has two modules that analyses the techno-economic viability of microgeneration systems. In the first module, the operational requirements are inserted by the user and the programme calculates the system performance based on the equipment characteristic curves for a wide range of variable operational conditions, i.e. altitude and local temperature, predicting the system efficiency for full or partial load. This module makes possible to evaluate the capacity of the system for meeting the user's demand concerning thermal and electric consumption.

In the second module, the economic analysis is performed through the cash flow construction of the proposed systems. The system's cash flow is used for calculating the Net Present Value (NPV) and the Internal Rate of Return (IRR). With this two obtained parameters, the programme plot graphs and yield relevant data for investment analysis in function of the market variables, i.e. exchange rate, electricity cost, and interest rate.

Table 1 – Proposed system characteristics (Enedis, 2001; Leon Heimer, 2003; Yazaki Energy, 2003a; Alpina, 2002)

Microturbine	
Specific Capital Cost	1200 USD/kW
Nominal Capacity	30 kW
Derating power for ambient temperature (32°C)	25 kW
Electric Efficiency	28%
Thermal Efficiency	50%
Capacity Factor	80%
Internal Combustion Engine	
Specific Capital Cost	560 USD/kW
Nominal Capacity	30 kW
Derating Power for Ambient Temperature (32°C)	30 kW
Electric Efficiency	31%
Thermal Efficiency	25%
Capacity factor	80%
Heat Exchanger Unit	
Specific Capital Cost	200 USD/kW
Nominal Capacity	45 kW
Effectiveness	60%
Water Outlet Temperature for a Single Microturbine Operation @ 2.4 kg/second	85.7 °C
Water Outlet Temperature for a Single Internal Combustion Engine Operation @ 2.4 kg/second	83.0 °C
Litium-Bromite Absorption Chiller and Cooling Tower	
Specific Capital Cost	1086 USD/kW
Nominal Capacity	35 kW
COP for a Single Microturbine Operation	0.52
COP for a Single Internal Combustion Engine Operation	0.50
Water Refrigeration Temperature @ 4.05 kg/second	29.5 °C

5. Case Study

For this paper was devised a scenario composed by two rooms. For the room one, a typical LAN house composed by 12 computers, lightening system, and mobile charges, was simulated. For the room two, a typical snack lounge composed by a fridge, a microoven, a TV set, and a blender was simulated. Table 2 shows the electrical and thermal demand for each room. For this simulation, the electric demand period was set for 24 hours a day, while the thermal demand was set for 12 hours a day. To attend the electric and thermal demand for the devised scenario, the proposed system is comprised by a microturbine or a internal combustion engine as prime mover, a heat exchanger for hot gases energy recovery, an litium-bromite absorption chiller, and a cooling tower. The cooling tower and the absorption chiller were considered one system and their individual capital cost were merged.

6. Acquired Technical Parameters

The annual fuel consumption is given by Equation (1):

$$E_f = \frac{P_{out}}{\eta_e} \times T \qquad (1)$$

Where the total operating hours for power production in a full operation regime (continuous operation for 365 days) is calculated by Equation [b]:

$$T_e = N_{days} \times N_{hours} \times C \qquad (2)$$

The thermal output capacity from the prime mover is given by Equation [c]:

$$Q_{th} = \left(\frac{P_{out}}{\eta_e} \right) \times \eta_{th} \qquad (3)$$

The thermal output capacity after heat recovering system is given by Equation [d]:

$$Q_{thr} = Q_{th} \times \varepsilon \qquad (4)$$

Hence, the refrigeration capacity is calculated by Equation [e] and the chiller manufacturer information about the COP (Yazaki Energy, 2003b):

$$Q_{ref} = Q_{thr} \times COP \qquad (5)$$

The annual power production is given by Equation [f]:

$$APP_{out} = T_e \times P_{out} \qquad (6)$$

The annual refrigeration production is given by Equation [g]:

$$ARP_{out} = T_r \times Q_{ref} \qquad (7)$$

The total operating hours for refrigeration production in a partial operation regime (12 hours a day operation for 365 days) is calculated by Equation [h]:

$$T_r = N_{days} \times N_{hours} \times C \qquad (8)$$

Table 2 – Case study energy demand.

Energy Demand	Room 1	Room 2	Total
Thermal	15 kW	7 kW	22 kW
Electric	21 kW	4 kW	25 kW

Table 3– Acquired System operational characteristics.

Microturbine as Prime Mover	
Annual fuel consumption	625 714 kWh
Total operating hours	7008 h
Thermal output capacity	44.6 kW
Thermal output capacity after heat recovering	26.8 kW
Refrigeration capacity	13.9 kW
Annual power production	175 200 kWh
Annual refrigeration production	48 806 kWh
Internal Combustion Engine as Prime Mover	
Annual fuel consumption	678 194 kWh
Total operating hours	7008 h
Thermal output capacity	24.2 kW
Thermal output capacity after heat recovering	14.5 kW
Refrigeration capacity	7.3 kW
Annual power production	210 240 kWh
Annual refrigeration production	25 432 kWh

7. Economic Viability Study

The price of electricity is 0.065 USD/kWh (with taxes) in Pernambuco State (CELPEa, 2003 & CELPEb, 2003). The total cost for consuming 25 kW in T_e = 7008 h is USD 11413 (R$ 39946). Assuming an average compressor refrigeration coefficient of performance of 1.5, the savings obtained from the production of 13.9 kW and 7.3 kW of cooling for a period of T_r = 3504 h is USD 2120 (R$ 7419) and USD 1105 (R$ 3866), respectively. Once both systems could not supply all refrigeration demand, the electricity consumed for produce the remaining cooling required for an equal period T_r is USD 1228 (R$ 4299) and USD 2243 (R$ 7852). For the financial analysis, the life time investment is 10 years and the depreciation method applied is for 10 years class equipment (Brigham et al, 2001). The maintenance factor was neglected as well as the costs with operational personnel. For the sensitivity analysis, a series of conditions were simulated, always considering a microturbine or an internal combustion engine as prime mover.

In the economic analysis a total of 3 market conditions were studied (see Conditions 1-3 in Table 5, based on the operational characteristics shown by Table 3. For the internal combustion engine (ICE) configuration, two options were analysed: one without selling the extra power production and the other selling the exceeding at 80% of the nominal price practised by the utility vendor. Both configurations have the same heat exchanger, absorption chiller and cooling tower. As shown by Table 1, the electrical demand considered is 25 kW and the thermal demand is 22 kW. The investment was analysed by using the Net Present Value (NPV) and Internal Rate of Return (IRR) criteria (Brigham et al, 2001). The NPV and IRR were calculated using Equations [9] and [10], respectively:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1-k)^t} \tag{9}$$

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1-IRR)^t} \tag{10}$$

The obtained economic results are shown by Figures 1-4, based on the capital cost presented by Table 5. Figure 1 shows the NPV analysis for 6 different conditions in function of interest rates ranging from 0 to 20%. It was simulated the curves for microturbine and ICE based systems, with two different exchange rates. It was also simulated conditions for the ICE system selling the exceeding power capacity. Figure 2 shows the annual savings for both systems in function of the variable interest rate and also present the curve for ICE system with the selling of the exceeding power capacity. Figure 3 shows the NPV curves in function of the variation of the exchange rate at a fixed interest rate of 12%. Figure 4 shows the IRR curves in function of the exchange rate variation for the proposed configurations.

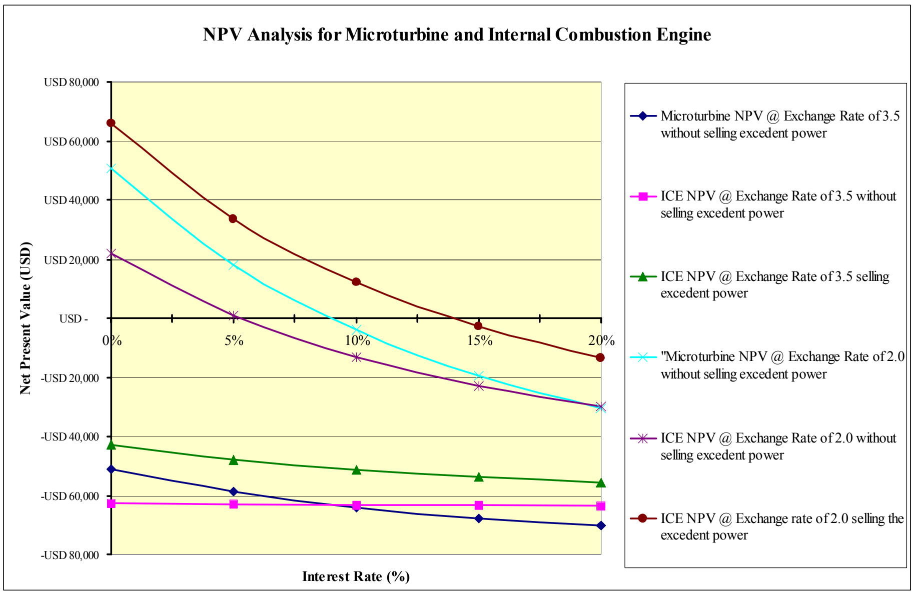

Figure 1 – NPV analysis for conditions 1 and 2.

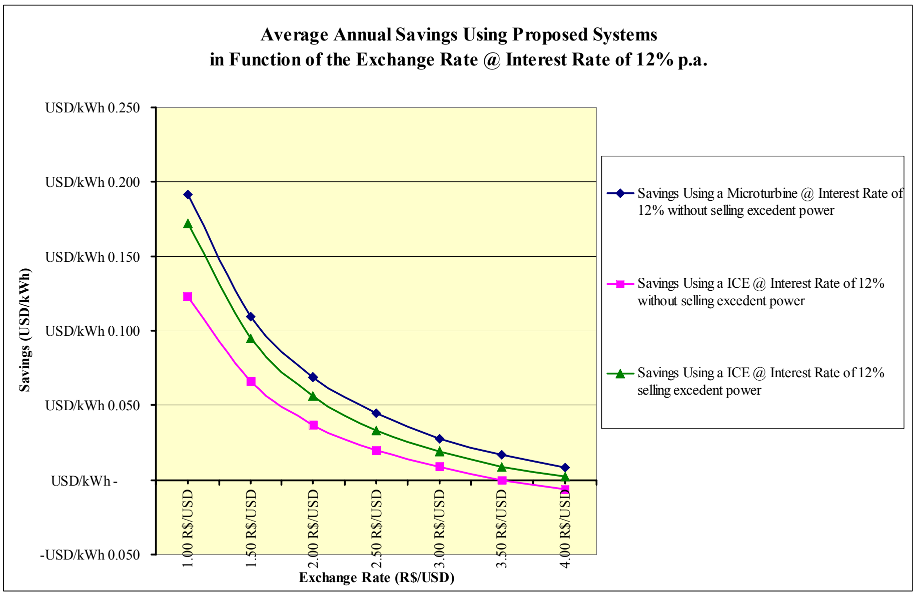

Figure 2 – Savings (USD/kWh) for the condition 3.

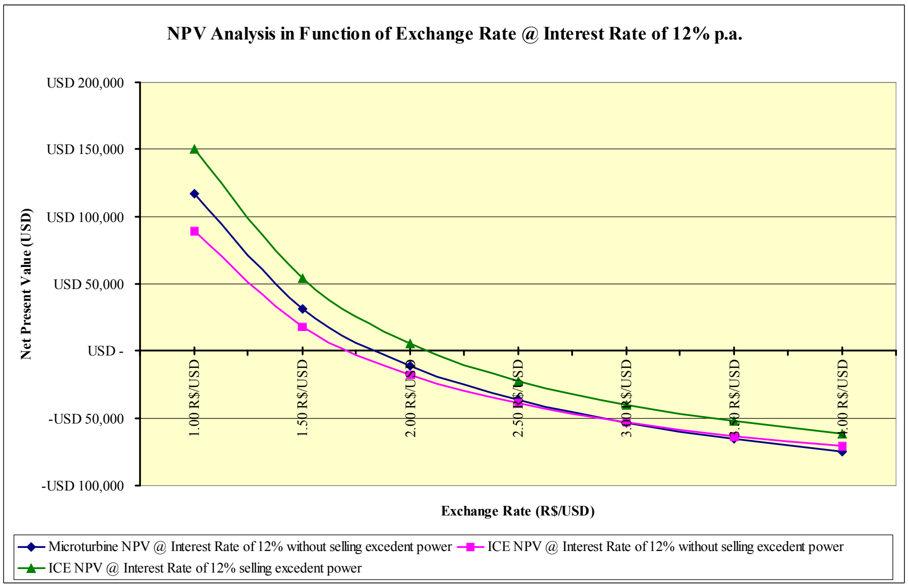

Figure 3 – NPV analysis for the condition 3.

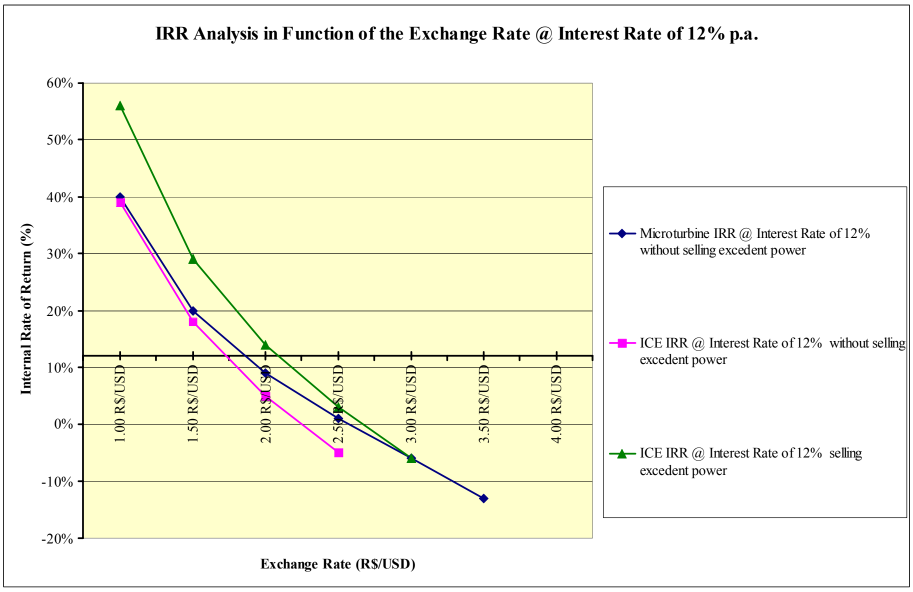

Figure 4 – IRR analysis for condition 3.

Table 4 – Specific Capital Cost of The Proposed Systems

Equipment	Brazilian National Currency (Real)	US Dollar
Capital Cost Microturbine ($/kW)	R$ 4200	USD 1200
Capital Cost ICE ($/kW)	R$ 1960	USD 560
Capital Cost Heat Exchanger Unit ($/kW)	R$ 700	USD 200
Capital Cost Absorption Chiller and Cooling Tower ($/kW)	R$ 3801	USD 1086

Table 5 – Conditions studied for the sensitivity analysis

Market Factor	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
Fuel Price (USD/kWh)	0.015	0.015	0.015	0.015	0.015-0.023
Exchange Rate (R$/USD)	3.5	2.0	1.0-4.0	2.0	2.0
Interest Rate (% p.a.)	0-20	0-20	12	12	6
Microturbine Capital Cost (USD/kW)	1200	1200	1200	300-1100	1200
ICE Capital Cost (USD/kW)	560	560	560	300-1100	560
Electricity Price(USD/kWh)	0.065	0.065	0.065	0.065	0.065

8. Sensitive Analysis

The sensitive analysis reproduced by Figures 5-8 is based on the conditions 4 and 5 from the Table 5. Figure 5 shows how the NPV varies in function of the specific capital cost at a constant exchange rate of R$ 2.0/USD and interest rate of 12%. Figure 6 shows the IRR variation in function of the specific capital cost at fixed exchange rate of R$ 2.0/USD, for a datum of 12% per annum. Figure 7 shows the NPV curves for variable fuel prices (condition 5 in Table 5 for a fixed interest rate of 6% and exchange rate of R$ 2.0/USD. The same analysis is performed for the IRR at a datum of 6% for the interest rate and the results are shown by figure 8.

10. Discussion

Analysing the NPV curves for either microturbine and internal combustion engines (see Figure 1), considering conditions 1 and 2, we notice that for an exchange rate of 3.5 R$/USD the investment is not recommended due to the net present values are negative. For an exchange rate of 2.0 R$/USD, the best investment is for the internal combustion engine option when is possible to sell the exceeding power. Otherwise, the microturbine option is more recommended and presents an internal rate of return of 9% against 5% from the internal combustion engine option. Microturbine options shows to be more economic than the internal combustion engine option, when power selling condition is not available. For exchange rate greater than 3.5 R$/USD, ICE utilisation without exceeding power selling yields negative cash flows. Microturbine also presents the better performance for annual savings (see Figure 2). When the interest rate is fixed at 12% p.a. and the exchange rate ranges between 1-4 R$/USD (Condition 3), the NPV curves are shown in the Figure 3. The microturbine option justifies the investment only if the maximum exchange rate is 1.8 R$/USD. The ICE option justifies the investment for maximum exchange rates of 1.7 R$/USD and 2.0 R$/USD, not selling exceeding power and selling exceeding power respectively. The IRR analysis for condition 3 can been seen in the Figure 4, taking the interest rate of 12% as datum. It confirms the conclusions concerning optimum exchange rate for justifying the investment of the proposed systems.

The sensitive analysis show that the use of microturbine technology for this devised scenario is viable for capital cost up to USD 800/kW. It will take some time for specific capital cost of microturbine reaches values under USD 800/kW. The use of ICE technology is cost-effective for present days, once its actual capital cost is around USD 500/kW. But for stand-alone applications, i.e. without selling the exceeding power, ICE configuration do not present itself as a good choice, whereas microturbine present better values of annual savings. ICE configuration with selling exceed power stands better the fluctuation of the fuel cost, being attractive for fuel prices up to USD 0.20/kWh. On the other hand, for stand-alone applications, this technology does not present itself any advantage in function of the fuel price. Microturbine configuration strengths its position as logical choice for stand-alone applications, presenting critical values for investment analysis only for fuel prices greater than USD 0.18/kWh.

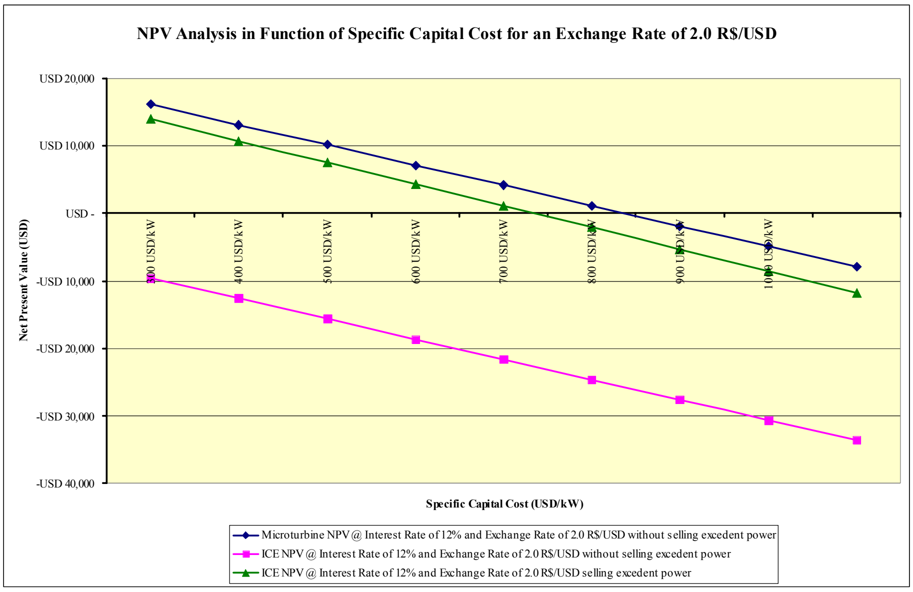

Figure 5 – NPV Variation in function of the specific capital cost (condition 4)

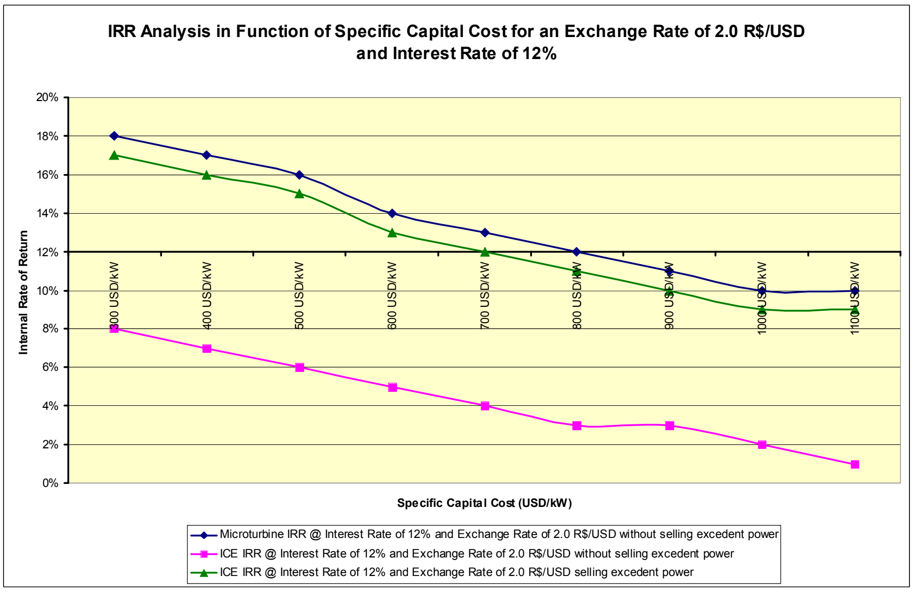

Figure 6 – IRR sensitivity analysis in function of the specific capital cost for an interest rate of 12% p.a. as datum.

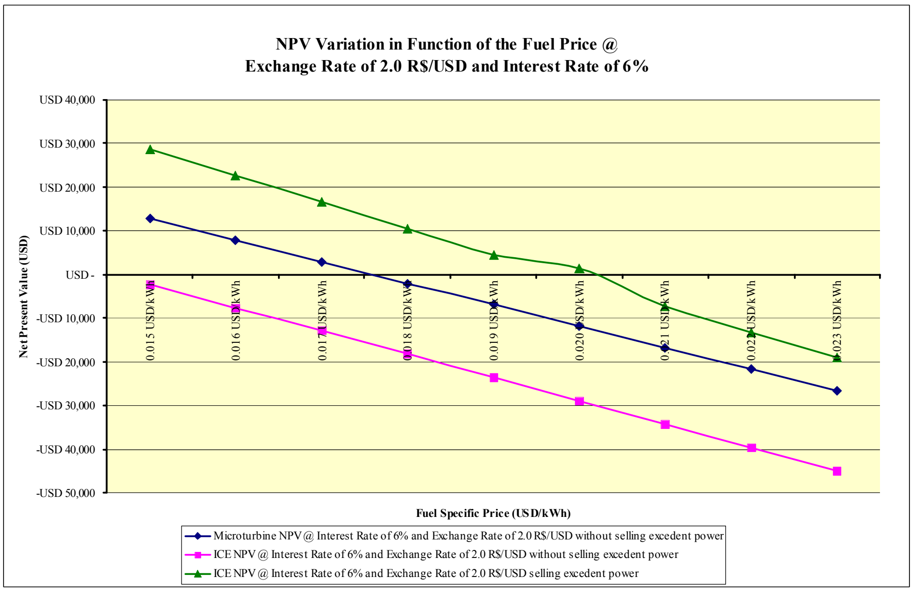

Figure 7 – NPV analysis in function of the specific fuel cost (condition 5).

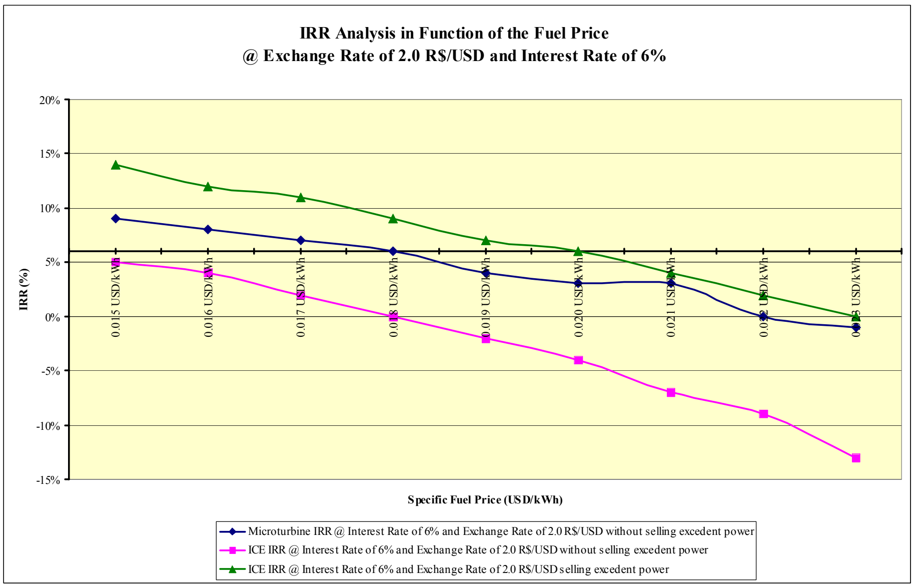

Figure 8 – IRR analysis in function of the specific fuel cost for an interest rate of 6% p.a. as datum.

11. Conclusions

This paper concludes that, for the devised scenario, micro-cogeneration is a viable alternative, once it generates positive cash flows for any of the proposed configurations. The maximum saving are obtained with microturbine technology configuration, while the best internal rate of return is achieved with ICE technology configuration, when there is exceeding power and it could be sold. For stand-alone applications, the preferred system is the one which uses a microturbine as prime mover.

These technologies are especially attractive for building service managers that targets the utilities cost reduction of their systems. Other alternatives to increase the thermal capacity of these proposed systems could be tried, such as the use of thermal storage system for cooling purposes. Hence, even for higher specific capital costs, microgeneration is a cost-effective alternative, that could be immediately implemented for utility cost reductions.

3. Acknowledgement

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6. Copyright Notice

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13. Nomenclature

APP_{out}	Annual system output power production [kWh]
ARP_{out}	Annual refrigeration output production [kWh]
C	Capacity factor [%]
COP	Absorption chiller coefficient of capacity
E_f	Annual fuel consumption [kWh]
N_{days}	Number of operating days [day]
N_{hours}	Number of operating hours per day [h/day]
P_{out}	Derating power output capacity for ambient temperature [kW]
Qref	Refrigeration capacity [kW]
Q_{th}	Thermal output capacity for prime movers [kW]
Q_{thr}	Thermal output capacity after heat recovering [kW]
T_e	Total operating hours for power production [h]
T_r	Total operating hours for refrigeration production [h]
E	Heat exchanger effectiveness [%]
η_e	Electric efficiency [%]
η_{th}	Thermal efficiency of the prime movers [%]
N	Investment life time
T	Period
K	Interest Rate
CF	Cash flow
NPV	Net Present Value
IRR	Internal Rate of Return