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COGENERATION SYSTEMS USING INTERNAL COMBUSTION ENGINES AND ABSORPTION CHILLERS

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ABSTRACT

The technical, environmental and economic viability of cogeneration systems, based on the use of natural gas internal combustion engine and an absorption chiller was investigated. Projects that meet the growing demand for diversification of energy supply in Brazil have already been well studied, but the alignment between modern regulation laws with the technologies available in the market for application in supermarkets is not well understood. The study method was divided in several phases: (1) the development of technical and economic indicator for general evaluation of projects; (2) the application of environmental indicator; (3) mapping of constraints and project requirements with regard to the legislation of qualified cogeneration; (4) the identification the electrical and thermal load in the case study; (5) modeling of the cogeneration plant for the case study; and finally (6) the evaluation of all identified indicators. The results present the best combinations for technical and economic application, the CO_2 emissions of these models and the viability of the system in a supermarket through the daily projection of energy billing and investment analysis. Such information is important because it presents a practical study for the application of cogeneration for one of the main commercial energy consumers in Brazil.

INTRODUCTION

In the last decade, the world has experienced several economic crises, from those caused by the inefficient use of natural resources to those caused by climate change. Even so, projections for world gross domestic product (GDP) growth remain promising, doubling in 2040, as emerging economies take more than 2.5 billion people out of poverty. As a result, strategies for efficient energy use and the reduction of pollutant emissions have been prominent in academic and corporate research (BP Energy, 2018).

This growing prosperity leads to an increase in global demand for energy, which could be offset by gains in energy efficiency in the period. In 2040, carbon emissions in Europe will be 35% lower than the 2016 period, due to frequent and mandatory policies to encourage more diversified and efficient energy generation (BP Energy, 2018).

Cogeneration offers an efficient approach to generating useful electrical and thermal energy, the latter used for heating and/or cooling of enterprises or industrial processes. Using only one energy source, these systems are increasingly being used as they are effective energy conversion power plants (EIA, 2018).

Despite being large emitters of CO_2, natural gas internal combustion engines (ICE), working in conjunction with absorption chillers, provide a substantial reduction in the emission of this pollutant, which ends up being proportional to the energy consumed by the chiller (Flórez-Orrego et al., 2014). Thus, cogeneration systems, when compared to conventional means of generation, are reputed to be highly efficient and provide an environmentally friendly generation with low greenhouse gas emissions (Moussawi et al., 2017).

In the case of absorption chillers, models that operate with ammonia and water provide temperatures up to -40^oC (Colonna and Gabrielli, 2003), while those operating with lithium bromide and water can only provide temperatures from 5^oC to 20^oC (Arteconi et al., 2009; Maidment et al., 2001). The work presented by Maidment and Tozer (2002), highlight the difficulty of finding chillers capable of operating small-scale cogeneration systems and offering negative temperatures.

The literature presents several works involving natural gas ICE associated to the most varied absorption chiller technologies. In addition, the low C/H ratio of natural gas contributes to low CO_2 emissions when compared to other fossil fuels such as diesel. Most of the results found by the researchers are directed towards a high energy efficiency, water supply at ideal temperatures for a good functioning of the cooling or heating system, and resulting reductions in the electricity bill of the simulated ventures (Ackermann et al., 2001; Colonna and Gabrielli, 2003; Sugiartha et al., 2009; Moussawi et al., 2017).

In this article, a method is presented to determine the limits of technical, economic and environmental feasibility for cogeneration plants using alternative ICE and an absorption chiller using natural gas as fuel. A real case study is used to demonstrate the application of the method and results are discussed.

METHODS OF ANALYSIS – GENERAL APPLICATION

The alternative ICE evaluated use natural gas as fuel and are sold in the Brazilian market with power ranging from 40 kW to 432 kW. The absorption chillers used have a cooling capacity of 30 to 87 TR, and are moved by hot water, steam or exhaust gas and are sold worldwide. Systems (models) that operate with a chiller moved by hot water or steam use an intermediate heat exchanger, while the exhaust gas chiller uses this energy source directly.

The system has the essential components of a functional plant, such as cooling towers, ICE, absorption chiller, safety valves and centrifugal pumps, as shown in Figure 1. The replacement water generated by evaporation, drag and purge was considered at 5% of the flow of the cooling stream (Inc. Betz Laboratories, 1991). The consumption of electricity from cooling towers and pumps was not taken into account. The coefficients of system performance (COP) used in this analysis for absorption chillers using steam, hot water and exhaust gases were 0.83, 0.81 and 1.36, respectively (World Energy, 2015).

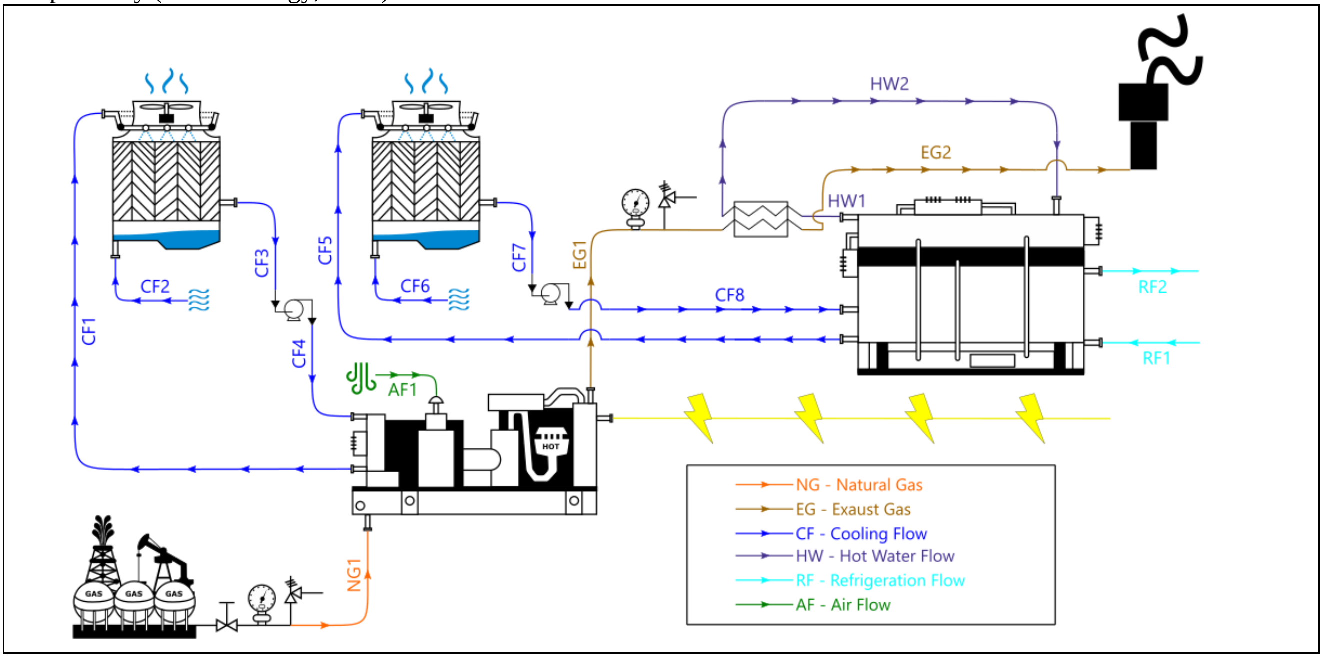

Figure 1: Model of proposed Energy Cogeneration System using a Heat Exchanger

Technical Indicator (Thermodynamic Adequacy between ICE and Absorption Chiller)

The technical indicator of thermodynamic adequacy (TA) is represented according to Equation (1). It shows the relationship between electric power (EP) and cooling capacity (CC). The reference temperature ($T_{Ref.}$) was considered at 120°C and the specific heat of the exhausted gas (Cp_{Eg}) at 1.18 kJ/kg.K (Garcia, 2013). The performance of the ICE (η_{ICE}) and the energy of fuel (E_{Fuel}) was based on the equipment of the manufacturer CHP Brasil. As a conservative hypothesis, it was also considered that the energy removed by the cooling system is not at suitable temperatures for working with the absorption chillers. The mass (m_{Eg}) and the temperature (T_{Eg}) of the exhausted gas was based on the chiller operating requirements (World Energy, 2015).

$$TA = \frac{EP}{CC} = \frac{E_{Fuel} \cdot \eta_{ICE}}{(m_{Eg} \cdot Cp_{Eg}(T_{Eg} - T_{Ref})) \cdot COP} \quad (1)$$

Figure 2 shows the application of the TA indicator in the cogeneration systems. For the three graphs, the thermodynamic adequacy line indicates that all the exhaust gas energy is being used to generate cooling, which represents the ideal combinations of cogeneration systems. The shaded region represents systems that have thermodynamic adequacy. Absorption chillers moved by hot water (a), steam (b) and exhaust gas (c) found on the market start with power of 30, 45 and 50 TR, respectively. The region below the guideline of chillers indicates technological restriction, because there is no commercial chiller to attend TA.

(a) (b) (c)

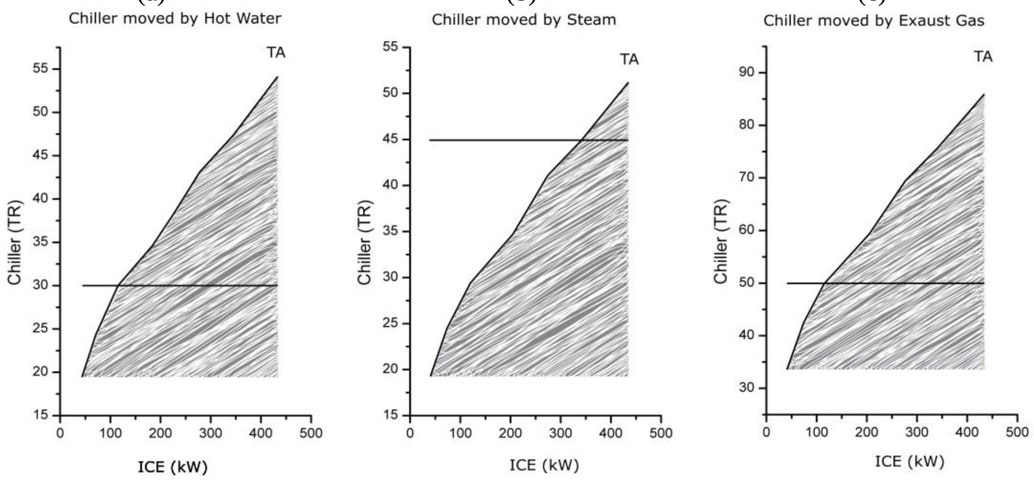

Figure 2: Application of the technical indicator of Thermodynamic Adequacy (TA)

The shaded region above the guideline of chillers represents the possible combinations that can compensate the energy if necessary. The non-shaded region (top of the graph) represents systems without thermodynamic adequacy (there is not enough residual energy to power the chiller). It is worth mentioning that the systems with chiller moved by steam are those with the greatest technological restrictions. Systems with a chiller moved by exhaust gas, as their COP values, are greater than those driven by hot water or steam. Also, they have higher cooling capacities for the same electrical power. This can be observed in the third graph, where the ideal line is offset upwards, when compared to the other models.

Environmental Indicator

The simulations for the application of the environmental indicator (amount of $kgCO_2$ per hour of operation) were carried out at each power level, but only those systems (models) that were functional by the TA indicator were considered for calculation. To compare with the emissions of the cogeneration models, a supermarket was considered using the power from the local supplier and cooling its food (thermal energy) with compression systems with COP equal to 3.

The results were associated with the Brazilian energy matrix in the years 2014, 2015 and 2017, which respectively emitted 131.62 tCO_2/GWh, 120.91 tCO_2/GWh and 93.39 tCO_2/GWh, according to the Greenhouse Gas Emissions Estimate System (SEEG). Figure 3 presents this final comparison and indicates that the cogeneration systems applied in Brazil are more polluting, if compared to the energy generated by the national matrix; regardless of the amount of electrical and thermal load required. The total energy from the graphs represents the sum of electrical power (EP) with the thermal energy of the models.

(a) (b)

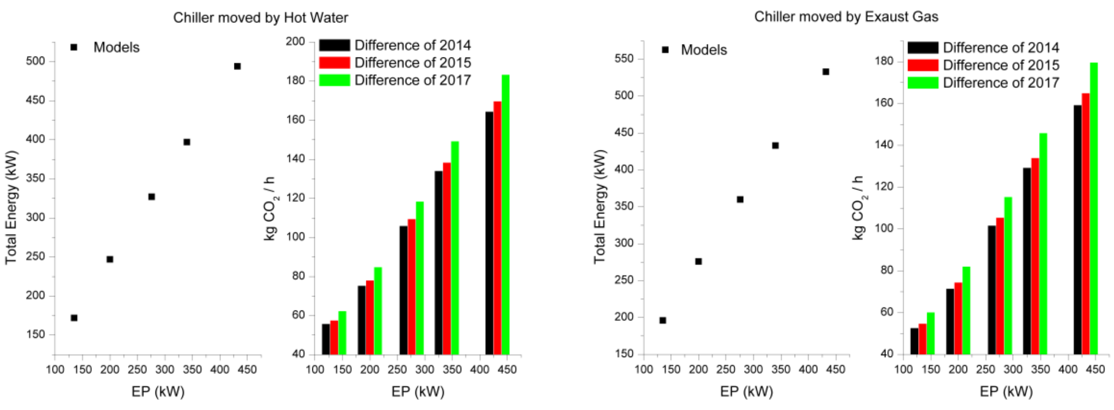

Figure 3: Difference in the CO_2 emission between the Cogeneration Models and the energy in the Brazilian Electrical Matrix

Our results are not in line with those presented by several researchers in cogeneration systems, who describe this type of energy generation as environmentally friendly (Maidment et al., 1999; Maidment and Prosser, 2000; Arteconi et al., 2009; Sugiartha et al., 2009; Isa et al., 2017; Moussawi et al., 2017). This is the result of a particularity of the Brazilian matrix which is basically composed of the hydroelectric generation of energy, which is much less polluting than the matrices of the home countries of the above mentioned researchers.

Economic Indicator

A common way to estimate the profitability of power generation through natural gas engines is to use the Spark Spread (SS) indicator. The main objective of this indicator is to reflect the financial stability of the generation plant and to gauge whether the enterprise should produce more or less energy (Elias et al., 2016). Its equation is presented in Equation (2) and involves the difference between the price of electricity (pEE in R$/kWh) and the price of generation involving natural gas (pNG in R$/kWh). Spark Spread positive means that the company is making money producing power with the system, with negative SS, the generation system is not economically favorable; in this case it is recommended to purchase energy from the supplier. For more information about SS we recommend Martínez and Torró (2018) and EIA (2018).

$$\text{Spark Spread} = \text{pEE} - \frac{\text{p NG}}{\eta\ \text{ICE}} \tag{2}$$

The SS does not consider the use of residual thermal energy, thus, for an economic analysis of cogeneration systems using an ICE and an absorption chiller, an adaptation of the Spark Spread was performed. Called VEO (Operational Economic Viability), the new indicator takes into consideration the contribution of thermal energy generation by the chiller (pTE) and the use of the exhaust gas of the ICE directed to the absorption equipment. The dimensionless constant 'R' is defined by the ratio of electricity price (pEE) and the price of energy generation involving natural gas (pNG). The VEO is represented according to Equation (3).

$$\text{VEO} = \left[\text{R} - \frac{1}{(\eta\ \text{ICE} + \eta\ \text{Chiller})}\right] .\ \text{pTE} \tag{3}$$

The results obtained with the VEO are presented in Figure 4, and the positive values indicate that the functional cogeneration models are economically favorable. The secondary cost of electricity to operate the ICE and the absorption chiller was not computed (pumps and fans). It is worth mentioning that systems operating with an exhaust gas chiller presented a VEO considerably larger than the other models because they have a higher COP.

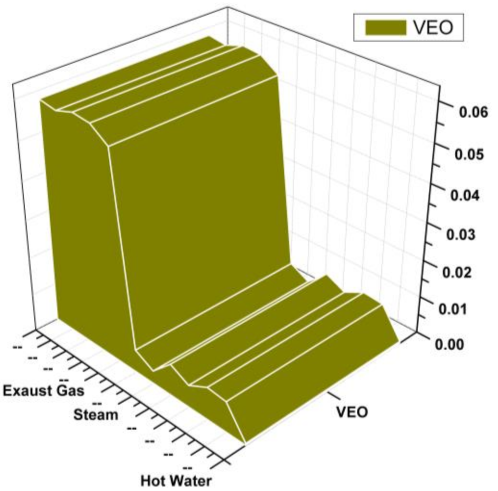

Figure 4: VEO for Energy Cogeneration Systems

The VEO is recommended for a daily analysis of the production of electric and thermal energy of cogeneration systems, considering the fluctuation in the prices of natural gas and electricity. The project manager can therefore make a quick decision whether to produce energy or even to suspend the operation of the system to buy electricity from the supplier. This indicator is not recommended for investment analysis because it does not consider maintenance costs, equipment purchase, cash flow, internal return rates among others.

CASE STUDY

The case study was developed in a typical and functioning supermarket, located in the metropolitan region of Salvador, Bahia, Brazil. With only one floor and a sales area of approximately 9,000 m^2, the enterprise operates 14 hours a day, every day of the week. In order to reduce electricity consumption during peak hours (6:00 p.m. to 9:00 p.m.), a diesel generator of 365 kW is activated during this period of higher tariffs.

Electricity consumption is based on the tariffs of high voltage customers (Group A), considering the green billing flag. Taking into account the contribution of the diesel generator in the peak hours of the supermarket, in a typical month of operation, the daily expenditure with electricity is approximately R$ 2,424.35; see Table 1. The cost of availability of contracted demand of 280 kW, with the supplier, was considered.

Table 1: Electricity bill for one month of high consumption (without cogeneration)

Energy (kWh)	Peak Hour (kWh)	Peak Hour Generation (kWh)	Off-Peak Consumption (kWh)	Difference (kWh)	Cost of Availability (R$)	Total Cost of Electricity (R$)
152,850	32,850	32,850	120,000	120,000	3,488.66	72,730.69

The supermarket operates with 26 '*Split*' air conditioning units, which are scattered throughout the enterprise and operate with diffusers that help cool the entire environment evenly. For maintenance, durability and safety in food sales, LTR's (Low Temperature Racks for Frozen Foods) and MTR's (Medium Temperature Racks for Colds) operate 24 hours a day, every day of the week. '*Split*' air conditioners cool the common areas, but only operate 14 hours a day i.e. the opening hours of the supermarket. The thermal load calculated of 78,196 kWh in energy per month for supermarket refrigeration is in line with the study presented by some researchers (Maidment et al., 2001; Marimón et al., 2011), which showed that this type of enterprise spends an average of 47% of the electricity on refrigeration.

To meet the electrical and thermal load of the supermarket, the main technologies available in the market were researched. The selected ICE operates with natural gas and has a power of 130 kW (*Prime Mover*). The chosen absorption chiller use hot water as a thermal power source, has a 30 TR cooling capacity, COP of 0.827 and operates with Lithium Bromide (LiBr) and Water. Its main function will be to provide the thermal load for the air conditioning system and the medium temperature racks (MTR) of the supermarket. Chillers with the capacity to supply negative temperatures and with adequate power for this supermarket were not found in the market, the same difficulty was found by Maidment and Tozer (2002).

The amount of total energy to service the computers, lighting and LTR (low temperature racks), which will not be served by the absorption chiller and will continue to operate with compression equipment (already in operation in the supermarket), we call this electric charge. The amount needed, in energy per month, to meet this requirement is 83,206 kWh. Figure 5 shows the model's operating scheme, with the ICE and chiller running 24 hours a day.

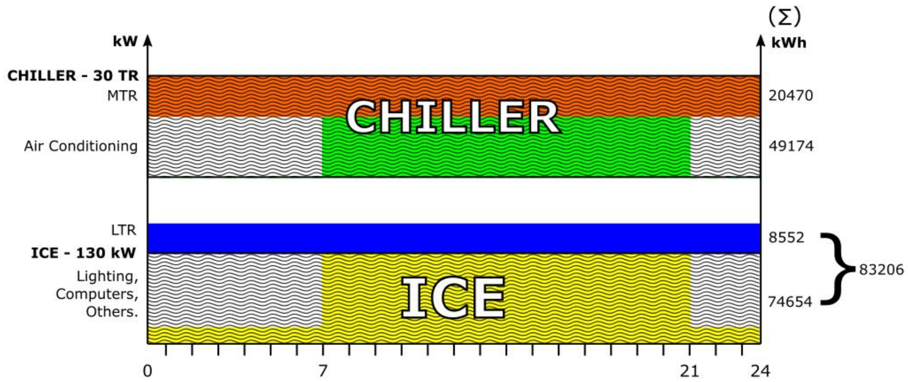

Figure 5: Scheme of use of the Cogeneration System

The proposed model complies with Brazilian legislation and is qualified, which means that the system is able to enjoy the benefits of qualified cogeneration (government incentives), such as compensation for the electricity produced. The TA indicator was equal to 1.21, which demonstrates that the model has an ideal thermodynamic equilibrium. The emission of carbon dioxide found was 78.5 kg CO_2/h, higher than the 22.7 kg CO_2/h, if the project did not have cogeneration and purchased the energy from the supplier. The positive VEO at 0.0005 (close to zero) means that the manager has to pay attention so that he does not miss opportunities to purchase electricity instead of producing.

The analysis of investment for deployment was favorable. Here it is assumed a lifetime of 20 years at a monthly discount rate of 3.3%. The electricity bill fell from R$ 72,730.69 to R$ 4,867.55. A monthly expense of R$ 24,473.34 for acquisition of natural gas was considered. With a positive net cash flow of R$ 453,020.16, the net present value (NPV) was R$ 300,245.79. The monthly internal rate of return (IRR) found was 6.2% and the discounted payback was 3.64 years.

CONCLUSION

This paper describes a technical study for the implementation of cogeneration systems based on a natural gas ICE and an absorption chiller with application in supermarkets. The study was carried out taking into account the incentive legislation in Brazil and follows the same direction as developed countries which have used cogeneration for decades as an efficient energy production alternative. The results presented in this study classify cogeneration systems that are feasible technically and economically favorable, through the analysis of the indicators that were developed as well as the amount of emissions of carbon dioxide of the models (kg CO_2/h). The case study in a supermarket met the legal eligibility requirements, which allowed the model to benefit from government incentives related to qualified cogeneration, which have resulted in a substantial reduction in the daily energy expenditure of the supermarket. The results of the investment analysis were favorable for implantation, with positive NPV, IRR at 6.2% and payback in 3.64 years. Thus, our results are in line with those presented by well-known researchers in the technological area, even though it is adapted to the local legislation of distributed generation with a focus on supermarkets; with the exception of the environmental indicator, which showed that these cogeneration systems in Brazil tend not to be environmentally friendly. As a suggestion of further research, we recommend studies of cogeneration systems using biomass as fuel. This model can present good results related to the environmental issue.

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