A Case Study of Exergy Modeling and Thermoeconomics of Cogeneration Plants Aiming the Tertiary Sector

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Abstract. *The tertiary sector of the economy uses electric energy in order to supply the needs of lighting as well as electric and thermal energy to produce cold air in air conditioning systems. In this context, cogeneration becomes important since it can produce both thermal and electric energy at the same time. The aim of this study is to quantify the installation and operational costs of cogeneration plants applied to malls. A comparative study was conducted between the energy cost of thermoelectric power plants and cogeneration plants, evaluating the most economic fuel applied to these plants. In addition, this study will briefly consider the ecological aspects related to cogeneration. Finally, a case study was conducted regarding a mall in the city of Belo Horizonte - Brazil that uses the following electric power demand - 4 MW. The results point out that the best fuel is directly related with the gross area of the mall, being the area that is illuminated and cooled.*

Keywords: *cogeneration, exergy, thermoeconomics, shopping centers, tertiary sector*

1. INTRODUCTION

Energy has a strategic position in society given that it can be considered an input essential for the realization of practically all human activities and economic development. Hence the importance of studies and projects that take into account the implementation and amplification of energy systems is comprehensible, on a level of generation as well as on a level of transmission and distribution. In the same manner, the incentives and the awareness towards the rise in the efficiency of its use can also be considered as an energy source in the sense that the more rational use permits the rise in the offer of energy or in the decrease of consumption. This results in almost always the decrease of energy service costs for the final consumer and for the electric sector.

Cogeneration is a technology that presents application potential in both the industrial and tertiary sector, in inter-connected systems as well as isolated systems, when there are no options of access for other forms of generation. Cogeneration distinguishes itself from the size of the systems already being used.

The service or tertiary sector of the economy includes the following segments: “shopping centers”, hotels, hospitals, supermarkets and commercial buildings. The service sector with which this study is particularly working with is “shopping centers”. The importance of this study stems from the possibility that businesses from this segment can reach energetic self-sufficiency, considering the prices for natural gas and for diesel oil, which are primary sources of fuel used by cogeneration, in comparison to the fees charged by the local energy concessionaries. According to the Brazilian Association of Shopping Centers the gross area of the “shopping centers” associated in Minas Gerais is approximately 250,000 square meters. Furthermore, in the study conducted by Poole & Poole (Poole e Poole, 2000), this value provides a potential for cogeneration estimated at 30 MW for all the associated “shopping centers.” It should be noted that this figure could be higher if one were to also consider the non-associated “shopping centers.” In this given context, this study emphasizes the use of this technology in the tertiary sector, specifically the “shopping centers” segments of the Minas Gerais economy, utilizing exergetic and thermoeconomic models in the analysis of the proposed potential systems. The study evaluates these systems through the lens of the 2nd Law of Thermodynamics which is concerned with the quantification of specific costs of electric energy and of thermodynamic currents throughout the process. The study also pays attention to the fuel used in each of the technologies chosen and, consequently its availability, seeking to vary the energy sources for cogeneration technology, in a manner that does not cause a dependency of a specific type of fuel.

2. COGENERATION APLLIED TO THE TERTIARY SECTOR OF THE ECONOMY

Cogeneration corresponds to the simultaneous production of different forms of useful energy, such as electromechanic and thermic energies, in order to supply the necessities of a unit of the process, be it the industrial, agricultural, commercial or isolated system sector, all through the same primary energy source (Balestieri, 2002).

In Brazil, the *shopping centers* segment is one of the most interesting for cogeneration until level 5MW. In fact, this was the first sector of service to apply cogeneration in the country, with units operating since 1992 in the “Ilha Plaza Shopping” and in “Norte Shopping,” both in the city of Rio de Janeiro (Poole e Poole, 2000).

The *shopping centers* present varied dimensions and in order to classify them this study will utilize GA (gross area) in square meters, as can be seen in Table 1 (Poole & Poole, 2000).

Table 1. Data regarding some *Shoppings Centers* affiliated to ASBRACE in Belo Horizonte / MG

Shopping Center	City/State	ABL (m^2)
BH SHOPPING	Belo Horizonte/MG	51000
DIAMOND MALL	Belo Horizonte/MG	11702
MINAS SHOPPING	Belo Horizonte/MG	32000
SHOPPING CIDADE	Belo Horizonte/MG	16000

2.1. Characteristics of Energy Consumption

In order to estimate the consumption of the electric energy, the electric potential, and the thermic potential of the *shopping centers,* a study was conducted (Poole & Poole, 2000) in certain units, taking into consideration the gross area (GA), the geographic location, the number of fixed stores, the conception of cold water, as well as other variables necessary for the creation of the indices used in the calculation of the electric and thermic charges.

Table 2. The intensity of annual electric use

Indices	Range of the Área (ABL) (x 1000 m^2)				
	< 10	10 a 20	20 a 30	30 a 50	> 50
Power (kW/m^2)	0,089	0,135	0,132	0,134	0,109
Total Consumption (MWh/m^2)	0,408	0,503	0,528	0,552	0,576
Air conditioning (MWh/m^2)	0,060	0,180	0,180	0,156	0,144
Illumination and others (MWh/m^2)	0,240	0,204	0,252	0,288	0,324
Consumption of the stores (MWh/m^2)	0,108	0,120	0,096	0,108	0,108

As defined above, cogeneration is the production of mechanical and/or electrical energy associated to the production of heat for a certain process. The heat generated from this process is the thermic base for cogeneration. In the case of *shopping centers* in Brazil and consequently in the state of Minas Gerais, this base is essentially composed by the demand for cold, in the form of cold water for the air conditioning systems. Instead of using chillers with electric compressors to produce cold water, it is possible to use absorption systems, where the heat created by the generator is capable of removing the heat from a given environment (Poole & Poole, 2000).

The absorption system first absorbs low pressure vapor in an appropriate absorbing liquid. During this process of absorption, the conversion of vapor into liquid occurs, similar to the process of condensation with the rejection of heat. The pressure of the liquid increases in a pump, and afterwards the vapor is released from the absorbing liquid through the transference of heat (Stoecker 1985).

2.2. Introduction to the Concept of Exergy

The word exergy comes from the Greek word ex (exterior) and ergon (force or work), or in other words it is the capability to develop work (Wall, 1998). According to Kotas (1995), exergy is a qualitative analysis of different forms of energy used in energetic balances in both thermic and chemical plants, indicating the maximum work that can be obtained in a process that utilizes environmental parameters as a state of reference.

The energetic method utilizes in its quantification analysis a calculation methodology called energetic balance, which has as its objective the means of evaluating the energetic efficiency of a system, where one can not only follow the currents of heat that transform into work but also evaluate how much of the heat was not utilized.

The exergetic method, therefore, allows one to analyze the qualitative aspect of a process or system in which heat transforms itself into work. In addition, this method allows one to find possible causes for the loss of the capacity for carrying out work and suggest solutions that seek to increase the exergetic efficiency of the system.

According to Bejan, et. al (1996), when the pressure, temperature, composition, velocity, or elevation of a determined system is different from those in the given environment, the capability for developing work exists. Since these given properties of the referred to system vary up until and including the environmental state, in the sense of having an equilibrium between the systems, this capacity can decrease. In the dead state, the conditions for mechanic, thermic and chemical equilibrium between the system and the environment are met.

According to Moran et al. (1996), the exergy balance for a closed system is developed by combining the balances of energy and entropy for the closed system. The formulations of the equations of energy and entropy used in these kinds of developments are respectively for a process of the thermodynamic state 1 to state 2:

$$E_2 - E_1 = \int_1^2 \delta Q - W \tag{1}$$

$$S_2 - S_1 = \int_1^2 (\delta Q / T)_b + \sigma \tag{2}$$

The term σ is the rate of production of entropy. By multiplying the equation of entropic balance by the temperature of the environment ($-To$) and by adding to the equation the energetic balance, one has the equation of the exergy balance that is valid for a control volume. The equation for a closed system would therefore be the following (Moran e Shapiro, 2002):

$$E_2 - E_1 = \int_1^2 (1 - T_0/T_b)\delta Q - [W - P_0(V_2 - V_1)] - T_0\sigma \tag{3}$$

By evaluating each term of equation 3, there is:
$E_2 - E_1$:the variation of exergy between the inlet and outlet currents; $(1 - T_0/T_b)\delta Q$: the transference of exergy associated to the heat that was exchanged; $[W - P_0(V_2 - V_1)]$: the transference of exergy associated to the work carried out; $T_0\sigma$: exergy destroyed.

The term P_0 is the atmospheric pressure and the term $(V_2 - V_1)$ is the difference of volume between the initial and final state.

The following equation can be considered the law of energy degradation due to the fact the one is able to quantify the reduction of capacity to carry out work. This is attributable to the occurrence of irreversible processes during the development of the processes of the conversion of energy of the system. In order to have a control volume the Gouy-Stodola theorem proposes the following relation:

$$I = T_0[\sum_{OUT} m_e s_e - \sum_{IN} m_i s_i - \sum_r (Q_r/T_r)] \tag{4}$$

As work, total exergy can be disaggregated in diverse forms of its manifestation:

$$Ex = Ex_c + Ex_p + Ex_f + Ex_o \tag{5}$$

where: $Ex_c = m(V_oV_o)/2$ => kinetic exergy; $Ex_p = mgZ$ => potential exergy ; Ex_f => physical exergy;
Ex_o => chemical exergy.

According to Kotas (1995), physical exergy is equal to the maximum amount of work obtained when a current of a substance is brought from its initial state to the environmental state, defined by the T_0, P_0 of a physical process that only involves thermic interactions with the environment. The equation for the physical exergy of a given substance at a determined state is as follows:

$$Ex_f = m[(h_1 - h_0) - T_0(s_1 - s_0)] \tag{6}$$

The above equation, when applied to two distinct states can be written as follows:

$$Ex_{f1} - Ex_{f2} = m[(h_1 - h_2) - T_0(s_1 - s_2)] \tag{7}$$

By Kotas' definition (1995), chemical exergy is equal to the maximum quantity of work obtained when considering a substance brought from its environmental state, defined by T_0, P_0, to its dead state. This occurs through processes involving the transference of heat and the mixture of substances only with the environment. The exergy of a gaseous mixture is the sum of the exergies of its components plus the work of compression:

$$E_{0m} = m(\sum_i e_{0i} + RT_0 \sum_i x_i \ln x_i) \tag{8}$$

Through an exergetic analysis it is possible to characterize, in a central potential, the manner in which available exergy in fuel is used and/or destroyed during the processes of energetic transformation. The exergy available is due to the burning of an energetic resource, or in other words, a combustible element which is used as an energy supply.
The exergetic efficiency, according to Kotas (1995) is given in the following equation:

$$\psi = (\sum \Delta E_S)/(\sum \Delta E_E) \tag{9}$$

in which ΔE_S represents the variation of exergy that is released and ΔE_E represents the variation of exergy that enters.

2.3. Thermoeconomics

According to Bejan et al. (1996), thermoeconomics is a field in engineering that combines the exergetic analysis to economic principles, in an attempt to provide the systems operator the information that is not available through thermodynamic and conventional economic analyses, but are essential for the project and the economic operation of a system. Vieira (1997) affirms that in a conventional economic analysis, the balance of costs expresses the association of the costs of inputs and of equipments necessary to obtain such costs. In this kind of economic analysis, the total cost of a product (C_P) is normally evaluated in the following manner:

$$C_{P,Total} = C_I + CC \tag{10}$$

In the above equation, the capital cost (CC) is taken as fixed, independent of the quantity of the manufactured good. The average per unit cost of a product is (C_I).

According to Tsatsanoris (1999), exergy is not an economic concept but a thermodynamic one. However, exergy can be applied in order to have a better understanding of a thermodynamic analysis because exergetic efficiency can be regarded as a generic index of the perfection of a process. Furthermore, it can serve as a general criterion in the evaluation of the capacity of thermoelectric installation or of the cogeneration of energy. Bejan et al. (1996) show the equation for the balance of costs formulated for a general system operating in a permanent regime:

$$C_{P,Total} = C_{F,Total} + Z_{I,Total} + Z_{OM,Total} \tag{11}$$

The sum of the last two terms is indicated by the variable Z:

$$Z = Z_{I,Total} + Z_{OM,Total} \tag{12}$$

According to Balestieri (2002), given that exergy measures real thermodynamic value and its effects, and that the costs C can only be associated to value *commodities*, the use of exergy is more appropriate as a base of costs. In that case, for each exergetic current of the entrance or exit of a volume of control, there is an association with the rates of the transference of exergy Ex_e e Ex_s, potential W, and the rates of the transference of associated exergy with the transference of heat Q. Hence, this can be written as follows:

$$\begin{aligned} C_S &= c_s Ex_s = c_s(m_s ex_s) \\ C_E &= c_e Ex_e = c_e(m_e ex_e) \\ C_W &= c_w W \\ C_Q &= c_q Q \end{aligned} \tag{13}$$

Thus the balance of costs, according to Balestieri (2002), comes down to the sum of the associated costs of the currents of exergy that are released with the costs of investments and the operation/maintenance and with the cost of the heat that is equal to the sum of the associated costs to the currents of exergy that enter with the cost of potential. This is:

$$\sum_E C_{E,K} + C_{W,K} = C_{Q,K} + \sum_S C_{S,K} + Z_K \tag{14}$$

In which the index K indicates the K-th component.

The application of a balance of costs implies a decision making process regarding the partitioning of costs, particularly in the system of energy cogeneration that generates two distinct products W e Q, in which the greater or lesser value of each one of these can help or not in the production for sale.

Balestieri (2002) claims that there are various criteria for the partitioning of costs, of which some are cited below:

- the extraction method: in this method one presupposes that all the exergy transferred by vapor, that enters the turbine (or by the escape gases, in a gas turbine), should be totally attributed to the portion of heat that is extracted from it. In other words, vapor has the same cost as fuel.
- the equality method: in this method one presupposes that the exergetic cost per unit of the electromechanic portion is equivalent to the portion of heat that was extracted from it. Or in other words that vapor has the same cost as the electricity generated.
- the electricity method: vapor does not have a value. The value is applied only to electricity. The plant for generation functions as a thermoelectric plant.

Given what has been presented thus far in this chapter, this study opted to evaluate cogeneration technologies destined at the service of the tertiary sector of the economy and related to the following systems: gas turbine associated to the Brayton Cycle, a motor gas associated to the Otto Cycle, and a diesel motor associated to the Diesel Cycle.

The fuels respectively used in these systems include: natural gas for the first two systems and diesel oil for the last. This decision has an approach that attempts to diversify the energetic field, being that the energy market is dependent on international prices.

3. METHODOLOGY OF EXERGETIC AND THERMOECONOMIC ANALYSIS

What follows is a description of a methodology for the application of exergetic and thermoeconomic methodology in a large *shopping center* in the city of Belo Horizonte for the configurations presented in Item 2.4. Table 3 shows the gross area and the total potential installed in this *shopping center* in the city of Belo Horizonte.

Table 3. The intensity of the annual energy use in *shopping centers*.

Gross Area (m^2)	Estimated Electric Potential (kW)	Estimated Thermic (Cold) Potential (kW)	Estimated Total Potential (kW)
30000	2500	1500	4000

3.1. Application of Cogeneration Models to the *Shopping Centers* Segment

In order for the analysis of cogeneration systems, presented in the previous item to be complete, it is necessary to introduce two equipments of extreme relevance for the correct establishment of a cogeneration system: a system of heat recuperation and a system that transforms this heat into cold.

With regard to the first equipment, this study presents as the solution a heat-recovery steam generator (hrgs). This equipment is intended to make use of the heat derived from exhaust leaving the turbine. In this boiler, the gases of combustion bring heat to the water and consequently this is transformed into vapor that leaves the boiler in this state.

The second equipment, previously described, is the system of refrigeration by absorption. According to (Poole & Poole, 2000), the absorption systems commonly found in the market are listed in Table 4.

Table 4. Operational conditions of absorption systems.

Equipments	Steam Conditions		COP
	Temperature (ºC)	Pressure (kPa)	
1 stage	110-120	35-103	0,60-0,70
2 stages	160-185	450-1000	0,90-1,20
3 stages	215	2000	1,55

In this specific study, a system of absorption is considered as that which has two stages, with a temperature of vapor at 185 ºC, vapor pressure of 1000 kPa, and a coefficient of performance – COP – of 1,20. The study is also taking into consideration that the system functions 365 days per year.

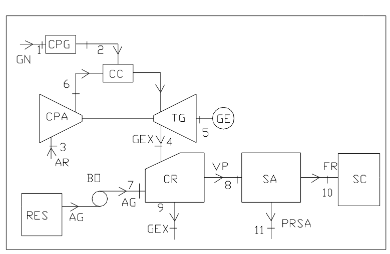
It should be noted that the hot vapor that is released from the heat-recovery steam generator (hrgs) serves as a hot source for the refrigeration system by absorption. Given the introduction of these two equipments in the system, it is necessary to have an exergetic and thermoeconomic model that serves these modifications.

In the following section, an analysis is done of the same systems, previously adopted: a gas turbine functioning in a Brayton cycle, a gas motor functioning in an Otto cycle and a fuel oil motor functioning in a Diesel cycle.

3.1.1. Gas Turbine

With the insertion of the heat-recovery steam generator (hrgs) and the absorption system, the layout of the cogeneration system with the gas turbine has the following arrangement as shown in Figure 1.

Figure 1. Basic Scheme of a Cogeneration System utilizing a Gas Turbine



Where: GN => natural gas; CPG => gas compressor; CC => combustion chamber; CPA => air compressor; AR => atmospheric air; TG => turbine of gas; GE => electric generator; GEX => exhaust gases; RES => reservoir; AG => water; CR => heat-recovery steam generator; SA => absorption system; BO => feeding pump; VP => vapor; FR => cold; PRSA => absorption system losses; SC => *shopping center*.

For the calculation of exergetic costs, a calculation of the discharge of vapor provided by the heat-recovery steam generator (hrgs) is done. Therefore:

$$m_8 = (Efic_{cr})(Ex_4 - Ex_9)/(Ex_7 - Ex_8) \tag{15}$$

The temperature of the exhaust gases of point 9 can be estimated at 450 K. The exergetic and thermoeconomic analysis is done based on Equation 14.
By applying this equation to the recuperation boiler and by adopting the simplifications laid out in Bejan et. al (1996), one will get the value of the cost of vapor:

$$c_8 = (c_4(Ex_4 - Ex_9)/(Ex_8) \tag{16}$$

By applying this equation to the absorption system and by adopting the simplifications laid out in Bejan et. al (1996), one will get the value of the cost of cold:

$$c_{10} = ((c_8)(Ex_8)/(Ex_{10}) \tag{17}$$

The total energetic efficiency can be calculated in the following manner:

$$\eta_{entotal} = (\eta_{en})(\eta_{cr})(COP) \tag{18}$$

The total exergetic efficiency can be calculated in the following manner:

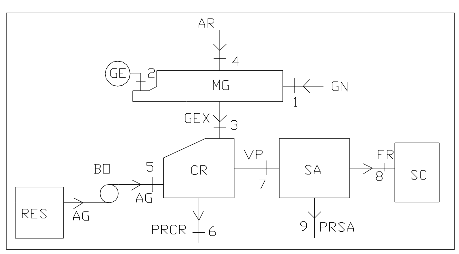
$$\eta_{extotal} = (FR + W + E_9)/(Excomb) \tag{19}$$

in which FR is the thermic demand for refrigeration in MW.

3.1.2. Gas Motor

With the insertion of the heat-recovery steam generator (hrgs) and the absorption system, the layout of the cogeneration system with the gas motor has the following arrangement as shown in Figure 2.

Figure 2. Basic Scheme for a Cogeneration System Utilizing a Gas Motor



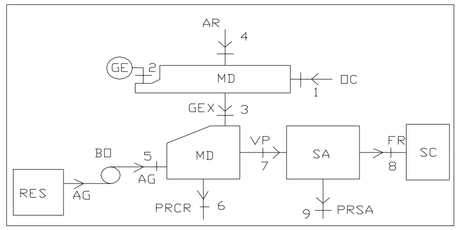
Where: GN => natural gas; MG => gas motor; AR => atmospheric air; GE => electric generator; GEX => exhaust gases; RES => reservoir; AG => water; CR => heat-recovery steam generator; SA => absorption system; BO => feeding pump; VP => vapor; PRSA => / absorption system losses; PRCR => losses of recuperation boiler; FR => cold; SC => *shopping center*.

The same model adopted for a turbine gas can be used for both a gas motor and a diesel motor.

3.1.3 Diesel Motor

With the insertion of the heat-recovery steam generator (hrgs) and the absorption system, the layout of the cogeneration system with the diesel motor has the following arrangement as shown in Figure 3.

Figure 3. Basic Scheme for a Cogeneration System Utilizing a Diesel Motor



Where: Onde: OC => oil fuel; MD => gas motor; AR => atmospheric air; GE => electric generator; GEX => exhaust gase; RES => reservoir; AG => water; CR => heat-recovery steam generator; SA => absorption system; BO => feeding pump; VP => vapor; PRSA => absorption system losses; PRCR => recuperation boiler losses; FR => cold; SC => *shopping center*.

Given the data obtained, each system is evaluated by three operating conditions i) a system operating at maximum capacity: 100% of the nominal potential; ii) a system operating at 90% of its maximum capacity; iii) a system operating at 75% of its maximum capacity.

It is important to emphasize that the prices adopted for natural gas and for oil fuel were obtained from the Belo Horizonte metropolitan distributors: GASMIG and PETROBRAS, respectively speaking. The prices of the equipments, the information pertaining to the maintenance and operation of the equipments, and replacement pieces for the equipment, etc., were all obtained by distributors throughout the country. Other equipment prices were used based on an estimation of the costs presented in Bohem (1987) and Bejan (1996).

The economic costs of the thermodynamic currents that run throughout the systems are also taken into account for the 100, 90 and 75% conditions of use of maximum nominal potential.

4. RESULTS

The results obtained for all of the configurations listed above are presented below, according to Table 5. The computational model was done using the EES (Engeneering Equation Solver) software, with the permission of the Mechanical Engineering Department of the Federal University of Minas Gerais (Departamento de Engenharia Mecânica da Universidade Federal de Minas Gerais).

Table 5. Configuration of a Gas Turbine

Configuration Charge Factor (%)	Equality Method		Extraction Method		Electricity Method	Energetic Efficiency of the Cogeneration Center (%)	Exergetic Efficiency of the Cogeneration Center
	Cost of Electricity US$/MWh	Cost of Cold US$/ton	Cost of Electricity US$/MWh	Cost of Cold US$/ton	Cost of Electricity US$/MWh		
100	42,50	2,68	29,95	1,89	77,06	36,60	46,47
90	46,86	2,28	32,33	1,57	83,37	36,60	46,11
75	53,90	1,97	36,72	1,35	96,46	36,60	45,00

Table 6. Configuration of a Gas Motor

Configuration Charge Factor (%)	Equality Method		Extraction Method		Electricity Method	Energetic Efficiency of the Cogeneration Center (%)	Exergetic Efficiency of the Cogeneration Center
	Cost of Electricity US$/MWh	Cost of Cold US$/ton	Cost of Electricity US$/MWh	Cost of Cold US$/ton	Cost of Electricity US$/MWh		
100	34,66	1,24	25,06	0,90	50,3	21,67	63,78
90	39,13	1,34	29,70	1,02	57,38	19,27	57,08
75	38,81	1,14	24,73	0,73	56,96	22,52	71,32

Table 7. Configuration of a Diesel Motor

Fator de Carga da Config. (%)	Equality Method		Extraction Method		Electricity Method	Energetic Efficiency of the Cogeneration Center (%)	Exergetic Efficiency of the Cogeneration Center
	Cost of Electricity US$/MWh	Cost of Cold US$/ton	Cost of Electricity US$/MWh	Cost of Cold US$/ton	Cost of Electricity US$/MWh		
100	37,14	0,29	25,15	0,20	46,45	25,78	76,00
90	38,87	0,27	25,30	0,18	48,61	25,75	78,61
75	42,20	0,24	25,46	0,15	52,79	25,66	84,14

5. CONCLUSIONS

The analysis of the results of the case study leads to the following conclusions:

- The application of thermoeconomic principles allows one to evaluate the costs of exergy currents used in each of the equipments being analyzed. This permits a clear identification and comparison between all the components and their effects on the final cost of the product. This evaluation leads to an objective form of identification of the components that have greater and lesser costs and therefore permits for an optimization process;
- The types of cogeneration systems, as well as the costs of generated energy, vary according to the gross area of the *shopping center*. The cost of electric energy from the concessionary is fixed, with a value of approximately US$60,00/MWh;
- For a *shopping center* with a gross area of 30,000 square meters, the most efficient system identified in this analysis is the gas motor with a cost of electricity at US$ 39,13/MWh;
- From a financial point of view, it is not worth building a thermoelectric plant for a *shopping center*, in the place of building a cogeneration plant since the cost of electric energy of the thermoelectric plants are higher than the cogeneration ones.

When a Diesel motor becomes more economically attractive to determine the gross area, it will be important to stress that it emits more atmospheric pollutants in its residual gases than a motor or turbine using natural gas. Environmental laws already established in the country enforce the use of fines during processes in which the emission of pollutants is above what is permitted. In order to abide by the requirements of the law, businesses should install equipments that control pollution, which implies additional expenses.

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7. RESPONSIBILITY NOTICE