ANALYSIS OF A SLAUGHTERHOUSE EXPANSION BY THE INTRODUCTION OF NATURAL GAS FOR ENERGY SUPPLY

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Abstract. *In this work the use of the natural gas as fuel for the simultaneous generation of refrigeration, electricity and steam for processes in a bovine slaughterhouse is analyzed. The studied configurations are the current plant, which uses a boiler with firewood for production of steam for processes, ammonia compressors for cooling and freezing and bought electricity, and modified plants that allow the use of the natural gas. For evaluation of the performance, energetic and exergetic analyses for each one of the configurations are carried out. It is also accomplished a thermoeconomic analysis that makes possible to evaluate the reflexes of capital investment and fuel costs in the composition products costs. Finally, an economical study based on the traditional techniques of economical engineering, as net present value and rates of return of the investment, is carried out. Analyzing the results and taking the case which uses traditional equipments for slaughterhouse, it is verified that the case which uses gas turbine, heat recovery steam generator and refrigeration by compression provides a small annual economy. Already for another case, which uses a gas turbine and absorption chillers, the annual investments overcomes that one of the base case, making impossible its implantation.*

Keywords*: Energy, trigeneration, natural gas, bovine slaughterhouse.*

1. INTRODUCTION AND OBJECTIVES

Nowadays cogeneration is the technique more extensively used for the combined production of electricity and heat. If refrigeration is produced simultaneously, then the process becomes trigeneration. The advantages of this technique are the economy of fuel, the increase of the efficiency and the reduction of environmental impacts.

This technique has been more used for systems of air conditioning. However, with the concerns about the atmosphere and conservation of energy, the trigeneration techniques are becoming more popular and becoming a potential solution for other applications, not only in the tertiary sector (shopping centers, hotels, hospitals, restaurants, etc.), as well as in the industrial sector (chemical industries, industries of foods and beverages, etc.).

The most recent technologies of trigeneration have been privileging the use of natural gas as fuel due to the reduced environmental impacts, motivating the utilization in others sectors. Particularly, it is outstanding the potentiality in the industrial sectors of foods and beverages for the implantation of trigeneration systems, once they present demands of heat, refrigeration and electricity.

So, the main objective of this work is to perform an analysis of the viability of implantation of trigeneration systems, utilizing natural gas as fuel in a bovine slaughterhouse. This study becomes important because it will allow the evaluation of the substitution of economically competitive fuels (firewood and, eventually, oil) by natural gas and avoiding the purchase of electricity.

Several conceptions of combined generation will be proposed and the viability of the installations will be discussed taking into account the overall energy consumed, the thermodynamic efficiencies, and the costs of the equipment, operation and maintenance.

There are several works in the literature about energetic, exergetic and economical analyses applied to thermal plants with the objective of developing alternatives for the energy efficiency increase and consequent reduction of electricity generation, steam and refrigeration costs, and among them can be cited some that contributed to the development of this work such as, for example, Kotas (1985), Bejan *et al.* (1996), Horlock (1997), Bruno *et al.* (1999), Maidment and Tozer (2002), Colonna and Gabrielli (2003), Minciuc *et al.* (2003), Calva *et al.* (2005), Takeshita *et al.* (2005). It has been noticed from the literature revision, that there is few information about applications of energy analysis to bovine slaughterhouses, showing a great opportunity for study in this field.

2. CASES DESCRIPTIONS

A Brazilian bovine slaughterhouse representing the industrial segment reality has been selected, in which the owners have interest in the natural gas utilization as fuel, taking advantages of Government's allowances for the increment of the use of this energy source and the proximity to the Bolivia-Brazil gas duct.

Today that industry process 1,250 bovines per day and there are two firewood boilers, with capacity of 10 t/h of saturated steam at 689.5 kPa each. However, just one boiler operates permanently to supply the industry needs, distributing steam to 8 digestors of 3,000 liters (0.5 ton/h for each), 4 digestors of 5,000 liters (0.5 ton/h for each), a heat exchanger that supplies 95°C water for processes (2.5 ton/h) and several steam extraction points (0.7 ton/h). Only the steam condensed from the digestors are recovered, leading to the need of supplying additional water to the cycle. The steam plant operates 14 hours per day and the firewood cost that supplies the boiler amounts to R$ 22.00/m^3.

The current plant uses the ammonia compression refrigeration cycles operating 24 hours per day. To supply the cooling loads in the range of -35°C/-10ºC, there is one 194 kW screw compressor with capacity of 1,025 kW. To supply the temperature in the range of -10°C/+35°C, there are six alternative compressors of 84 kW, with total load capacity of 1,956 kW. There are two more compressors installed in this last regime (-10°C/+35°C) to supply the condensation load of the other regime (-35°C/-10ºC), because the refrigeration cycles were projected to operate in "*booster*" mode. One of these compressors is a 291 kW screw compressor with refrigeration capacity of 1,084 kW and the other is an 84 kW alternative compressor with refrigeration capacity of 326 kW.

The current electricity demand of the plant is approximately 3,000 kW and almost 45% of that is related to the refrigeration plant. This demand is supplied by an electric company at the cost of R$ 0.24/kWh.

The slaughterhouse intends to increase its production up to 2,500 bovine per day, not only operating almost 24 hours per day for 6 days per week (7,000 hours per year), but also employing some modifications in the plant, configurations to be proposed, in order to supply the steam, refrigeration and electricity demands, resulting in the following cases.

2.1. Case 1: Plant with boiler supplied by firewood and refrigeration by ammonia compression

The steam plant proposed in Case 1 is constituted by the current steam plant of the slaughterhouse (Fig. 1) because this part of the plant attends the new demand, just by increasing the number of hours of operation from 14 to 24 hours per day. The refrigeration plant considered in this case and also in the next case is composed by the current plant of refrigeration and an additional one with the same characteristics (Fig. 2), complementing the capacity of the current plant. Note that, although the slaughterhouse processes 1,250 bovines per day, the current refrigeration plant has capacity for almost 1,500 bovines. Thus, the additional cooling plant to be installed must supply a new production (1,000 bovines), needing 2/3 of the current refrigeration capacity. In this case, total demand of electric power increases from 3,000 kW to 5,000 kW. Table 1 shows some operational parameters for Case 1.

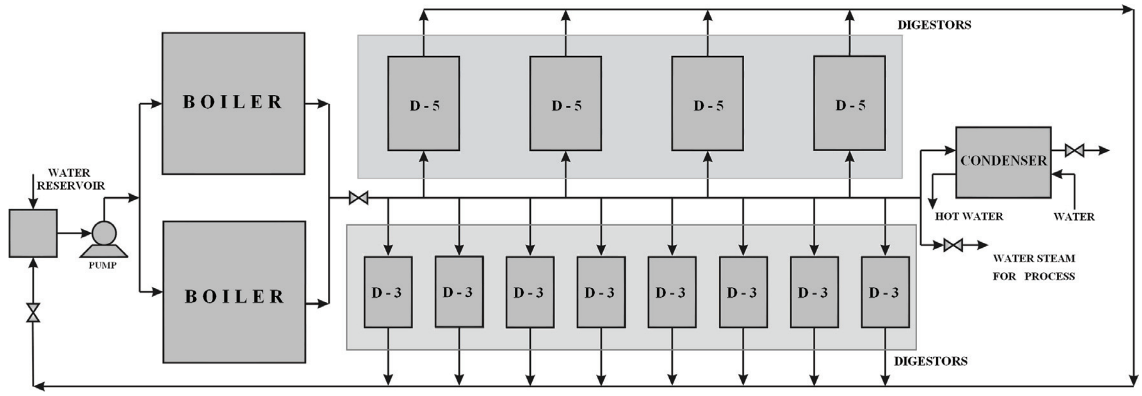
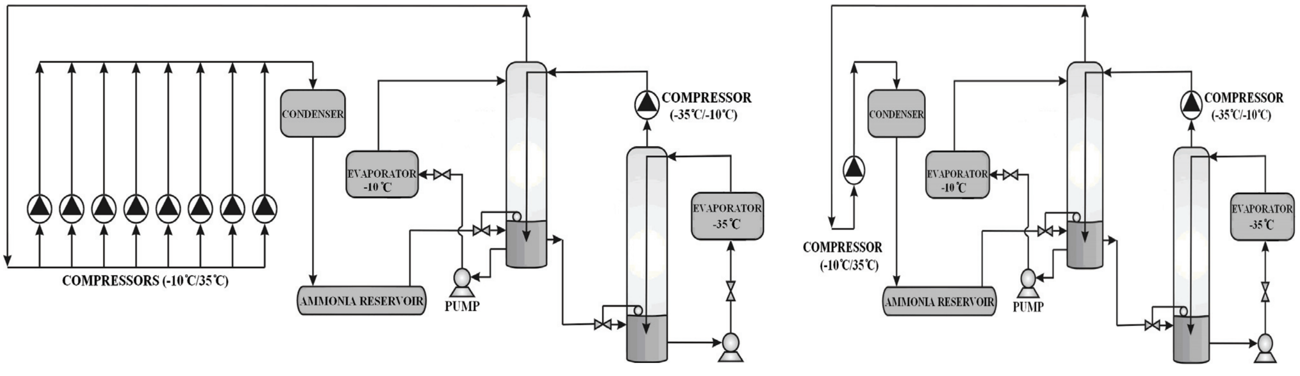


Figure 1. Plant for steam production by using firewood boiler (Case 1).



(a) Current Refrigeration Plant (b) Additional Refrigeration Plant

Figure 2. Plants for refrigeration production by means ammonia compression (Cases 1 and 2).

Table 1. Operational parameters for Case 1.

Firewood Boiler Plant		Refrigeration Plants	
Pump efficiency	70%	Sub-cooling temperature of condenser	5°C
Firewood Lower Heat Value	10.467 kJ/kg	Temperature variation between separator and compressor	5°C
Pressure drop at boiler	15%	Condensation temperature	35°C
Boiler efficiency	75%	Pump efficiency for -10/35°C operation	70%
Firewood density	280 kg/m^3	Pump efficiency for -35/-10°C operation	70%

2.2. Case 2: Plant with gas turbine, heat recovery steam generator and refrigeration by compression

In the Case 2, a gas turbine installation is proposed so that the slaughterhouse will produce all electric energy demanded. So, an Alstom Power turbine (model Typhoon 5.05) with capacity for production of 5,044 kW has been chosen. Thus, the slaughterhouse stops buying electric energy and to buy natural gas at R$ 0.50/m³. Besides, the firewood boilers replaced by a heat recovery steam generator with one pressure level that produces steam using the exhaust gases from gas turbine. The plant for steam and electricity production of the Case 2 (Cogeneration System) is presented in Fig. 3. The refrigeration plant of Case 2 is the same utilized in Case 1 (Fig. 2), but in this case the energy demand is supplied by the electric generator coupled to the gas turbine. Table 2 shows some operational parameters for Case 2.

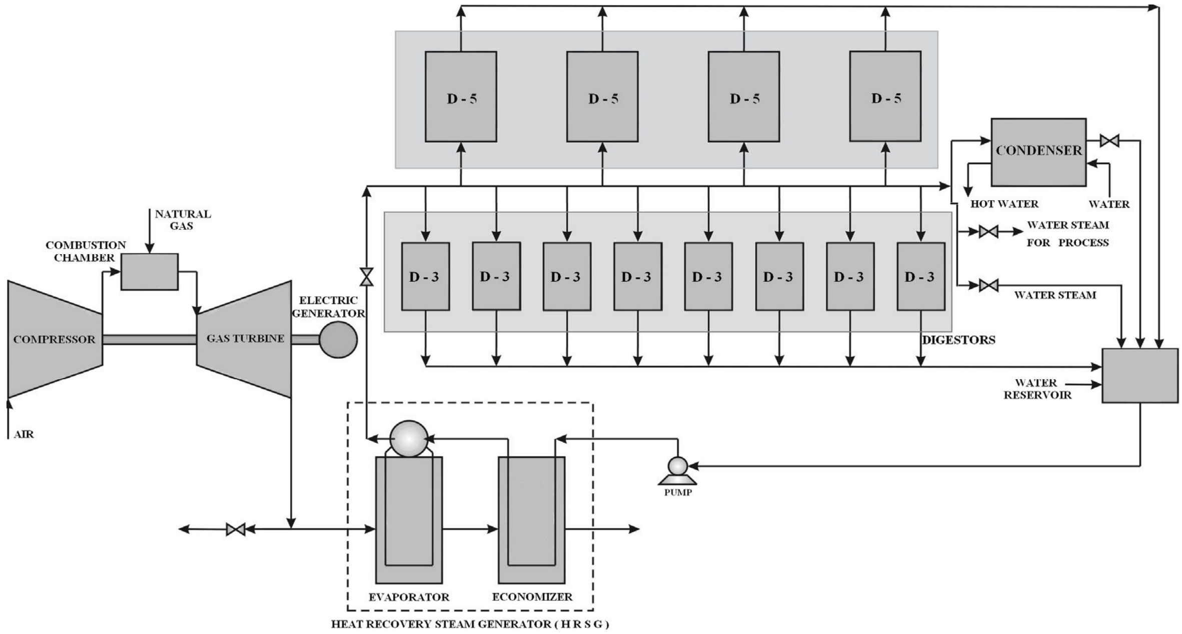


Figure 3. Plant for steam and electricity production by using gas turbine and heat recovery steam generator (Case 2).

Table 2. Operational parameters for Case 2.

Gas Turbine		Heat Recovery Steam Generator	
Isentropic compressor efficiency	87%	Approach	15°C
Exhaustion gases mass flow	19.54 kg/s	Pinch point	25°C
Compression rate	14.7	Heat exchanger efficiency at evaporator	75%
Power produced by gas turbine	5,044 kW	Pressure drop of exhaustion gases at evaporator	0.05%
Combustion chamber efficiency	80%	Pressure drop of steam at evaporator	2%
Pressure drop at combustion chamber	2%	Heat exchanger efficiency at economizer	75%
Electric generator efficiency	95%	Pressure drop of exhaustion gases at economizer	0.05%

2.3. Case 3: Plant with gas turbine, heat recovery steam generator and refrigeration by absorption chiller

In the Case 3, a new gas turbine installation is proposed for production not only of steam and electricity, but also for simultaneous production of refrigeration by means of water-ammonia absorption chillers (Trigeneration System), which operate with exhaust gases from turbine, according to Fig. 4. A Mitsubishi turbine (model MF-111) with capacity of 15.450 kW, that permits electricity surplus for sale, has been selected. Absorption chillers are installed for the evaporation temperature of -35°C and -10°C, respectively. Table 3 shows some operational parameters for Case 3.

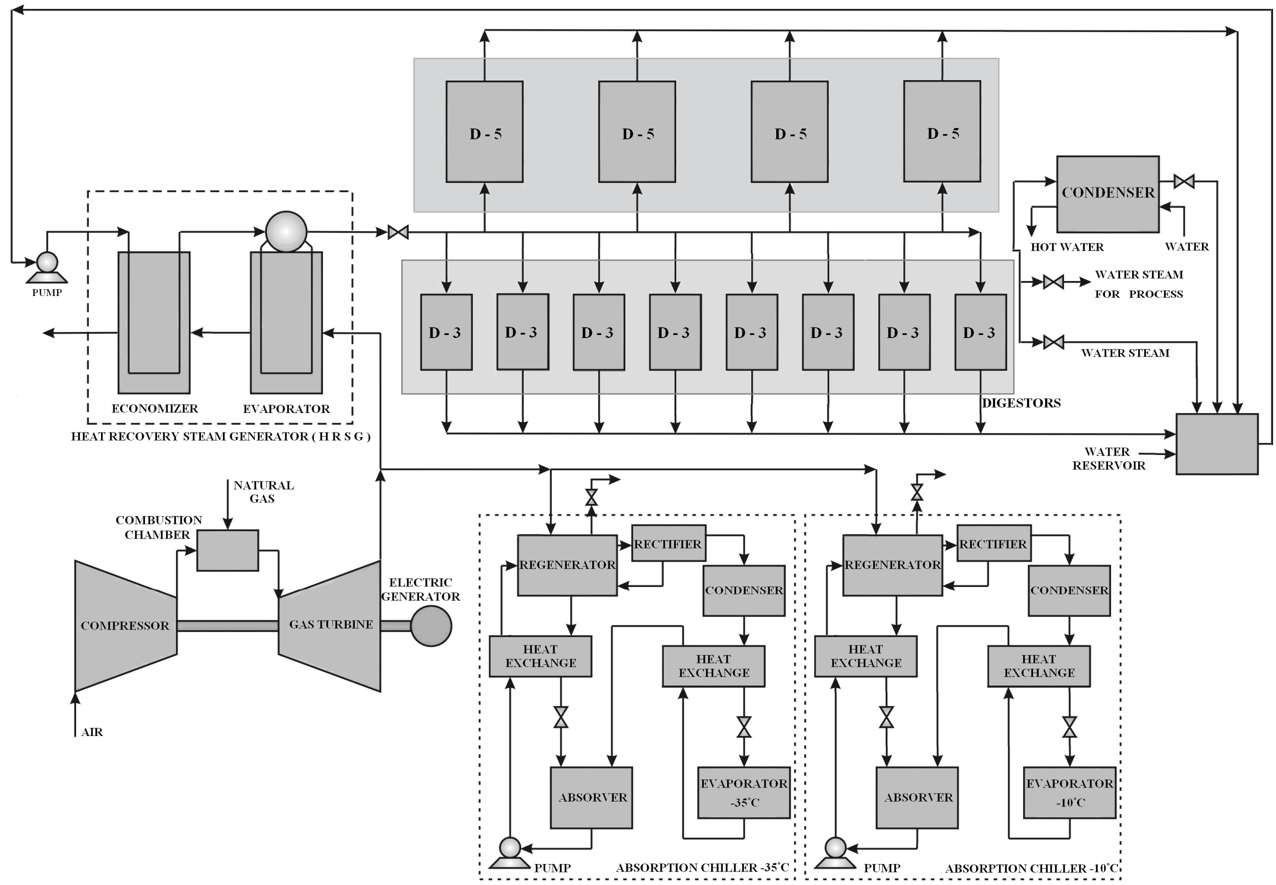


Figure 4. Plant for steam, electricity and refrigeration production by using gas turbine, heat recovery steam generator and absorption chiller (Case 3).

Table 3. Operational parameters for Case 3.

Gas Turbine		Absorptions Chillers	
Isentropic compressor efficiency	87%	Heat exchanger efficiency	85%
Exhaustion gases mass flow	55.4 kg/s	Condensation temperature	30°C
Rate compression	15	Power demanded by chiller -35°C	1,708 kW
Power produced by gas turbine	15,450 kW	Power demanded by chiller -10°C	3,260 kW

3. METHODOLOGY

Firstly, the energetic and exergetic analyses of the plants must be accomplished, considering a control volume for each one of the equipments. In general, for processes in steady state and neglecting the variations of kinetic and potential energy, the thermodynamic equations can be expressed as:

$$\sum_{i=1}^{n} \dot{m}_{in} - \sum_{i=1}^{n} \dot{m}_{out} = 0 \tag{1}$$

$$\sum_{i=1}^{n} \dot{Q}_{cv} - \dot{W}_{cv} + \sum_{i=1}^{n} \dot{m}_{in} h_{in} - \sum_{i=1}^{n} \dot{m}_{out} h_{out} = 0 \tag{2}$$

$$\sum_{i=1}^{n} \dot{Q}_{i} \left(1 - \frac{T_0}{T_i} \right) - \dot{W}_{cv} + \sum_{i=1}^{n} \dot{m}_{in} ex_{in} - \sum_{i=1}^{n} \dot{m}_{out} ex_{out} = \dot{I}_{cv} \tag{3}$$

where: $\dot{m}$ - Mass flow rate (kg/s); $\dot{Q}$ - Heat flux (kW); $\dot{W}$ - Power (kW); h - Specific enthalpy (kJ/kg); ex - Specific exergy (kJ/kg); $\dot{I}$ - Irreversibility rate (kW).

The specific exergies in the entry and exit mass flow for all equipment are expressed, respectively, by:

$$ex_{in}=\left(h\text{-}h_o\right)_{in}\text{-}T_o\left(s\text{-}s_o\right)_{in} \tag{4}$$

$$ex_{out}=\left(h\text{-}h_o\right)_{out}\text{-}T_o\left(s\text{-}s_o\right)_{out} \tag{5}$$

where: ex - Specific exergy (kJ/kg); h - Specific enthalpy (kJ/kg); s - Specific entropy (kJ/kg K).

The first and second thermodynamic laws efficiencies (η and ψ) are evaluated for each equipment through the following expressions:

$$\eta=\frac{\dot{W}}{\dot{m}\,\Delta h_{iso}} \tag{6}$$

$$\psi=\frac{\Delta h_{real}}{ex_{in}\text{-}\,ex_{out}} \tag{7}$$

where: η - First law efficiency (%); ψ - Second law efficiency (%); $\dot{W}$ - Power (kW); $\dot{m}$ - Mass flow rate (kg/s); Δh - Enthalpy difference (kJ/kg), ex - Specific exergy (kJ/kg).

For natural gas specific exergy evaluation, the following equation is used:

$$ex_{ng}=ex_{phy}+ex_{chem} \tag{8}$$

The physical and chemical natural gas exergies (taking it as ideal gas) can be calculated, respectively, by:

$$ex_{phy}=\left(h\text{-}h_o\right)\text{-}T_o\left(s\text{-}s_o\right) \tag{9}$$

$$ex_{chem}=\left(\sum_{i=n}x_i\,\overline{Ex_i}^{o}+\overline{R}\,T_0\sum_{i=n}x_i\,lnx_i\right)\Bigg/\left(\sum_{i=n}x_i\,M_i\right) \tag{10}$$

where: i - Index for the gas components; M - Molecular mass; x - Mass molar fraction (%); $\overline{Ex_i}^{o}$ - Standard chemical molar exergy (kJ/kmol); $\overline{\text{R}}$: Universal gas constant.

Table 4 shows the standard chemical exergy for the natural gas components at $T_0 = 298.15$ ºC and $P_0 = 1$ atm, according to Szargut *et al.* (1988).

Table 4. Standard chemical exergy of the natural gas components.

Component	$\overline{Ex_i}^{o}$ (kJ/kmol)
Methane (CH_4)	836,510.00
Ethane (C_2H_6)	1,504,360.00
Propane (C_3H_8)	2,163,190.00
Pentane (C_5H_{12})	3,477,050.00
Carbon Dioxide (CO_2)	20,140.00
Nitrogen (N_2)	720.00

After thermodynamic analysis, a thermoeconomic study for determination of the production costs is carried out. The exergetic cost theory presented by Bejan *et al.* (1996) has been the methodology employed in this work.

The exergetic cost analysis usually involves the cost balances formulated separately for each component. A cost balance applied to a component "k" of system shows that the sum of cost rates associated with all outlet exergy flux is the same as the sum of cost rates for all inlet exergy flux, plus the sum of capital investment, operation and maintenance expenses ($\dot{Z}_k$). Thus, for a component that receives heat and generates power, the result is:

$$\sum_{out}\left(c\dot{Ex}\right)_k + c_{W_k}\dot{W}_k = c_{Q_k}\dot{Ex}_{Q_k} + \sum_{in}\left(c\dot{Ex}\right)_k + \dot{Z}_k \tag{11}$$

where: c - Exergetic specific cost (R$/kJ); $\dot{Ex}$ - Exergy rate (kW); $\dot{W}$ - Power (kW); $\dot{Z}$ - Equipment cost rate (R$/s).

For definition of investment costs in equipments and for economic analysis it was considered an annual interest rate of 12%; useful life of 20 years; operation and maintenance costs of 10% of the capital and 7,000 hours/year of operation.

The costs of the new equipments were estimated according to Modesto (2004) and World Gas Turbine Handbook (2001-2002) and also based on the information of manufacturers or distributors The total investment in the plants is estimated according to the acquired equipments costs (AEC) and is presented in the Table 5 (Bejan *et al.*, 1996).

Table 5. Estimative of the total investment in the plants.

Investment	Value
Acquired equipment costs (AEC)	100% AEC
Acquired equipment installation	45% AEC
Pipeline	20% AEC
Instrumentation and control	23% AEC
Electrical equipments and materials	11% AEC
Installation area	0% AEC
Structural and architectural services	20% AEC
Auxiliary installations	65% AEC
Engineering and supervision	30% AEC
Civil construction	42.6% AEC
Eventual costs	37.5% AEC
Plant start-up costs	27.6% AEC
Total	421.7% AEC

The costs should be amortized during the useful life of the plant. Thus, the value to be amortized can be calculated using the formulation proposed by Bejan *et al.* (1996):

$$A = VI\left[\frac{j(1+j)^N}{(1+j)^N - 1}\right] \tag{12}$$

where: A - Amortization value (R$); j - Annual interest rate (%); VI - Investment value.

Taking into account the amortization period, the interest rate and the period of operation, the annual amortization rates ($\dot{Z}$) for each one of the equipment. The specific exergetic cost of the fuel is evaluated by:

$$c_{comb} = \frac{C_{comb}}{Ex_{comb}} \tag{13}$$

where: c - Specific exergetic cost (R$/kJ); C - Total cost (R$); Ex - Exergy (kJ).

For the solution of the resulting equations system has been used the program EES® (Engineering Equation Solver), allowing the determination of the thermodynamic properties of the system, such as enthalpy and entropy, facilitating the accomplishment of the calculations in a simple and efficient way, without thermodynamic tables. The adopted reference state has the temperature of 25 ºC and pressure of 101.3 kPa.

4. RESULTS

Tables 6 to 8 present some data for each equipment, such as efficiencies, electric power (demanded or produced), heat rate exchange demand and irreversibility for each case studied.

Table 6. Efficiencies, electric power, heat rate and irreversibility for each equipment for Case 1.

Equipment	η	ψ	$\dot{W}_{cons}$ (kW)	$\dot{Q}$ (kW)	$\dot{I}$ (kW)
Current steam plant					
Pump	0.70	0.74	2.9	-	0.8
Boiler	0.75	0.23	-	6,866.0	7,064.0
Digestors D3	0.75	-	-	248.5	82.8
Digestors D5	0.75	-	-	347.9	116.0
Heat Exchanger	0.75	0.26	-	1,242.0	364.7
Current refrigeration plant					
High pressure compressors	0.75	0.81	84.0	-	16.0
Booster compressor	0.75	0.81	291.0	-	55.6
Low pressure compressor	0.62	0.66	194.0	-	66.4
Evaporative condenser	-	-	-	4,089.0	-
Evaporator -10°C	-	-	-	1,956.0	-
Evaporator -35°C	-	-	-	1,025.0	-
Additional refrigeration plant					
High pressure compressors	0.75	0.81	586.3	-	112.1
Low pressure compressor	0.62	0.66	129.3	-	44.3
Evaporative condenser	-	-	-	2,723.0	-
Evaporator -10°C	-		-	1,304.0	-
Evaporator -35°C	-	-	-	683.3	-

Table 7. Efficiencies, electric power, heat rate and irreversibility for each equipment for Case 2.

Equipment	η	ψ	$\dot{W}_{cons}$ (kW)	$\dot{W}_{prod}$ (kW)	$\dot{Q}$ (kW)	$\dot{I}$ (kW)
Gas turbine						
Compressor	0.87	0.94	7,570	-	-	429
Combustion chamber	0.80	0.82	-	-	6,648	4,549
Nozzle	0.82	0.93	-	12,879	-	1,021
Electric generator	0.95	-	-	5,044	-	265
Heat recovery steam generator						
Evaporator	0.75	0.45	-	-	6,258.0	2,460
Economizer	0.75	0.57	-	-	390.6	1,915

Table 8. Efficiencies, electric power, heat rate and irreversibility for each equipment for Case 3.

Equipment	η	ψ	$\dot{W}_{cons}$ (kW)	$\dot{W}_{prod}$ (kW)	$\dot{Q}$ (kW)	$\dot{I}$ (kW)
Gas turbine						
Compressor	0.87	0.94	22,162	-	-	1,221
Combustion chamber	0.80	0.82	-	-	-	13,177
Nozzle	0.82	0.93	-	37,925	-	3,001
Electric generator	0.95	-	-	15,450	-	813
Heat recovery steam generator						
Evaporator	0.75	0.44	-	-	6,258.0	2,460
Economizer	0.75	0.57	-	-	390.6	1,915
Absorption Chiller -35°C						
Pump	0.70	0.97	20.04	-	-	0.20
Heat exchanger 1	0.85	0.99	-	-	1,678	7.74
Desorber	0.85	-	-	-	3,110	-
Reflux cooler	-	-	-	-	1,751	-
Condenser	-	-	-	-	722.9	-
Heat exchanger 2	0.85	0.99	-	-	128.1	0.97
Evaporator	-	-	-	-	683.3	-
Absorber	-	-	-	-	1,327	-
Absorption Chiller -10°C						
Pump	0.70	0.97	33.44	-	-	0.33
Heat exchanger 1	0.85	0.99	-	-	2,429	10.18
Desorber	0.85	-	-	-	3,455	-
Reflux cooler	-	-	-	-	1,114	-
Condenser	-	-	-	-	1,362	-
Heat exchanger 2	0.85	0.99	-	-	126.7	0.32
Evaporator	-	-	-	-	1,304	-
Absorber	-	-	-	-	2,296	-

The performance coefficient (*COP*) has been evaluated for each refrigeration plant. While absorption chillers cycles for loads of -10°C and -35°C in Case 3 present *COP* of, respectively, 0.38 and 0.22, the cycle of refrigeration by compression in Cases 1 and 2 present *COP* of about 2.78 .

For the thermoeconomic analysis, the total capital investment, the annual maintenance and operation costs and the annual amortization for each plant of the Figures 1 to 3 are presented in Tab. 9.

Table 9. Costs of investment, maintenance, operation and amortization for each plant studied.

Case	Total Capital Investment (R$)	Annual Maintenance and Operation Costs (R$)	Annual Amortization (R$)
Fig. 1	-	36,000.00	36,000.00
Fig. 2a	-	132,000.00	132,000.00
Fig. 2b	3,710,960.00	88,000.00	584,819.00
Fig. 3	19,049,499.00	451,731.00	3,002,055.00
Fig. 4	95,726,375.00	2,270,012.00	15,085,742.00

So, the monetary costs calculated through the thermoeconomic analysis for each case studied are presented in Tab. 10. Table 11 exhibits the annual expenses for steam, refrigeration and electricity production for each case.

Table 10. Monetary costs for steam, refrigeration and electricity production.

Costs	Case 1	Case 2	Case 3
Steam (R$/ton)	25.90	46.38	45.97
Refrigeration (R$/MWh)	107.0	70.63	879.80
Electricity (R$/MWh)	240.00	139.10	137.10

Table 11. Annual expenses for steam, refrigeration and electricity production (millions R$).

Expenses	Case 1	Case 2	Case 3
Firewood	1.73	-	-
Electricity	8.40	-	-13.35
Natural gas	-	6.14	18.67
Annual amortization	0.59	3.59	15.08
Total	10.72	9.72	20.41

Figure 5 presents the influence of natural gas cost in the annual investment for each case studied.

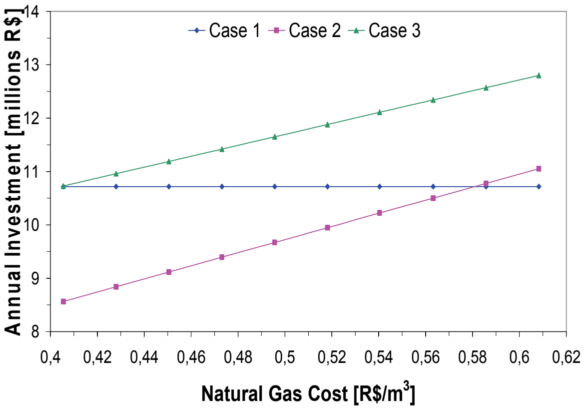


Figure 5. Annual investment versus natural gas cost.

The total investment capital was estimated based on the values presented by Bejan *et al.* (1996) like presented in Tab. 5 and Fig. 6 presents the influence of this factor in the annual investment for each studied case.

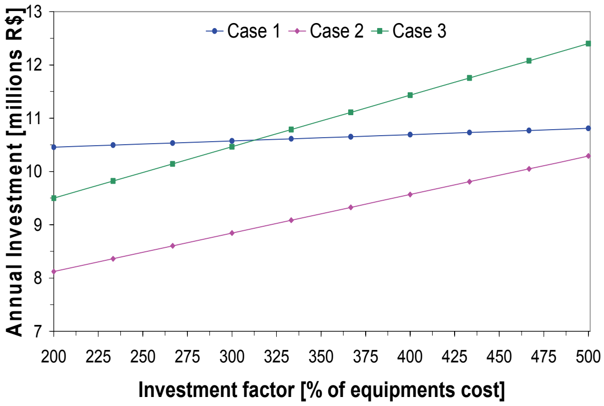


Figure 6. Annual investment versus investment factor.

5. CONCLUSIONS

Analyzing the results presented in Table 11 and looking at the Case 1 which uses traditional equipments for slaughterhouse as reference, it is verified that the plant in Case 2 would provide an annual economy of R$ 1 millions. Thus, in this case, there is the feasibility for natural gas utilization through the gas turbine installation coupled to a heat recovery steam generator. However, in Case 3, which uses gas turbine, heat recovery steam generator and absorption chillers, the annual investment overcomes that one of the Case 1, making not recommended its implantation due to the high costs of new equipments, principally the absorption chillers costs.

Nowadays the company pays around R$ 240.00 per MWh to supply the electricity demand. Considering cases where electric energy has been self-produced, it can be noticed that the costs to generate energy by natural gas in Cases 2 and 3 are, respectively, R$ 139.10 and R$ 137.10 per MWh. This point is a positive factor to choose between conventional installations or cogeneration, or even trigeneration, configuration for bovine slaughterhouses.

While comparing refrigeration systems in this work, refrigeration systems compressor-based are more indicated than absorption chillers. Despite of COP's between both systems, absorption chillers are more expensive that conventional plant compressor-based. Perhaps chillers become attractive when there is some heat source in the local of cogeneration system application.

Changes in natural gas cost presented in the Fig. 5 have much influence in the Case 2 since that configuration employs more natural gas than the Case 3. As the Case 1 does not use natural gas, the annual investment does not change with this variation.

The total capital investment for each case was estimated according to Bejan *et al.* (1996). The Fig. 6 shows that for all investment factor, the Case 2 would need a smaller annual investment than Cases 1 and 3. If the investment factor is smaller than 312.5 % of equipment costs, the Case 3 would have an annual investment smaller than in the Case 1. However, a better estimative of total capital investment could be obtained through better cost estimative of each plant component.

It is believed that for new slaughterhouse designs based on modern equipment technologies, considering the installation near the pipeline and the integration with factories of sub-products, the use of natural gas can be quite feasible.

6. ACKNOWLEDGEMENTS

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