# NATURAL GAS COGENERATION PLANT FOR AN AUTOMOTIVE INDUSTRY IN BRAZIL

**José Alexandre Matelli, matelli@feg.unesp.br**
**Daniel Hagestedt Ferreira, dhferreira86@gmail.com**
UNESP – Univ Estadual Paulista, Department of Energy, Guaratinguetá, SP – Brazil

***Abstract.*** *The search for energy efficiency improvement is a common concern in many companies. Cogeneration is a well known energy conservation technique. In Brazil, biomass cogeneration plants are widely spread; on the other hand, natural gas plants are not so common, specially in the industrial sector. In this work, a preliminary technical and economic study is carried out for a cogeneration plant application in an automotive industry located in São Paulo. Three 2435 kW generator sets based on reciprocating internal combustion engines are selected to generate power. The heat associated to the engines exhaust gases are recovered to generate steam. When compared to the current status (no cogeneration), annual savings of about 2,3 MR$ are expected, resulting in an almost 3 years payback.*

***Keywords****: Cogeneration, Natural gas, Automotive industry, Internal combustion engine.*

**NOMENCLATURE**

| | |
|---|---|
| $E$ | Generated energy (MWh/year) |
| $F_c$ | Cogeneration factor (–) |
| $I$ | Investment (MR$) |
| $L$ | Mover load (–) |
| $N$ | Number of operating movers (–) |
| $\dot{Q}$ | Heat demand; heat transfer rate (kW) |
| $R$ | Revenue (MR$/year) |
| $T$ | Temperature (°C) |
| $\dot{W}$ | Power output (kW) |
| $X$ | Weighting factor (–) |
| $c_p$ | Specific heat (kJ/kgK) |
| $h$ | Enthalpy (kJ/kg) |
| $k$ | Interest rate (%) |
| $\dot{m}$ | Mass flow (kg/s) |
| Greek letters | |
| $\eta$ | Efficiency (–) |
| $\rho$ | Specific mass (kg/m³) |
| Subscripts | |
| $c$ | Condensate |
| $e$ | Electrical |
| $ec$ | Economizer section |
| $ev$ | Evaporator section |
| $f$ | Fuel |
| $g$ | Exhaust gases |
| $l$ | Saturated liquid |
| $m$ | Prime mover |
| $n$ | Nominal |
| $o$ | Overall |
| $p$ | Pinch point |
| $s$ | Saturated steam |
| $st$ | Stack |
| $t$ | Thermal |
| Acronyms | |
| $DPB$ | Discounted payback (years) |
| $IRR$ | Internal rate of return (%) |
| $LHV$ | Lower heating value (kJ/m³) |
| $NPV$ | Net present value (MR$) |

## 1. INTRODUCTION

Cogeneration is a well known energy conservation technique. Most of cogeneration plants applied in the Brazilian industrial sector uses biomass, due to the large availability of this fuel in both sugar/ethanol and pulp & paper industries. Several studies of such applications are widely available in the literature, such as Ensinas et al (2009, 2007), Marshman et al (2010) and Cortés and Rivera (2010), to name a few. Natural gas cogeneration plants, on the other hand, are not so common in the Brazilian industry, including the metal manufacturing sector. However, some discussions about incentive policies in order to change these scenarios are presented by Szklo et al. (2004).

In general, metal manufacturing industries do not present demand profiles suitable for cogeneration, since their power demand profile are quite different from their heat demand profile, in terms of both magnitude and temporal trend.

Nevertheless, the literature presents some works for this application (Ozalp and Hyman, 2006; Sala et al., 2008). Studies of a cogeneration plant for and automotive industry in Brazil is presented by Coelho (2001) and Ribeiro (2004). In both works, it is considered the generation of hot water as utility. In the present paper, it is proposed a cogeneration plant for power and steam generation in an automotive industry located in São Paulo. The plant is conceived based on the actual energy demand data from the factory. Its performance is computationally simulated considering both prime mover data and energy demand data. A preliminary economic analysis is performed in order to quantify the potential energy cost reduction of this application.

## 2. ENERGY DEMAND DATA

The factory has a plant for utility distribution composed of two natural gas boiler (one for backup) and one electric boiler, also for backup. Saturated steam is generated at an absolute pressure of 1,1 MPa. The condensate returns to the boiler at the same pressure, but at a temperature of 90 °C. The steam flow is measured hourly by the boiler operator. The power demand is measured automatically every 15 minutes. The steam and power demand data composes a comprehensive and up-to-date database. This is a unusually favorable situation, since in most cases the thermal demands must be estimated due to the lack of registered data (Orlando, 1996).

The factory data related to an one year period (from September 2010 to August 2011) are collected and consolidate in Fig. 1. The demands shown in Fig. 1 refers to the median of the values at each hour of each day. Since the thermodynamic states of the saturated steam and returning condensate are known, the steam demand can be calculated through Eq. (1):

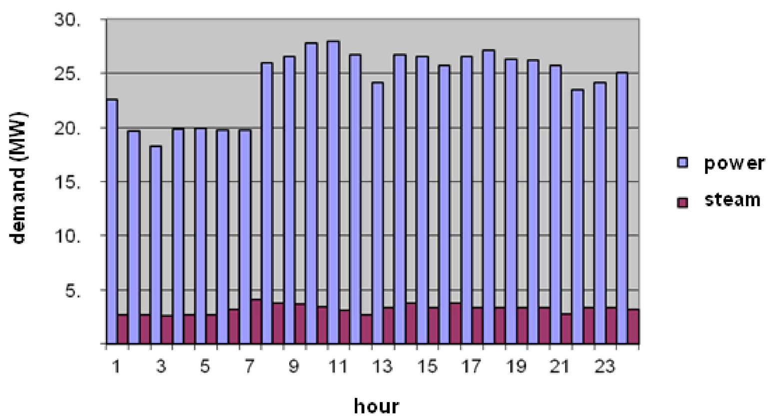


Figure 1. Power and steam demand

$$\dot{Q}_s = \dot{m}_s \left( h_s - h_c \right) \tag{1}$$

It is clear from Fig. 1 that the power demand is much greater than the steam demand. Thus, the heat-match strategy for plant operation is recommended. The plant is designed to meet all the steam demand, so that the power generated contributes to reduce the power demanded from the grid. If the power-match strategy were adopted, there would be a significant exceeding heat that should be rejected to the environment, compromising the overall efficiency.

## 3. COGENERATION PLANT DESCRIPTION AND MODELING

The proposed cogeneration plant is shown in Fig. 2. Three reciprocating engine-based generator sets Waukesha 12V275GL+ are selected as prime movers. The nominal power output of each generator set is 2435 kW. The heat associated to the engines exhaust gases are recovered in a heat recovering steam generator (HRSG). The plant should operate in heat-matching mode, i.e., the generator sets are selected so that the heat from the exhaust gases is enough to generate all the steam required from the processes of the factory. The current utility plant becomes part of the new cogeneration plant for backup purposes.

The part-load performance of the prime mover is taken into account based on the manufacturer data. The regression from these data for $0,5 \leq L \leq 1,0$ results in Eqs (2-4), which relates the mover load to the efficiency, exhaust gases mass flow and exhaust temperature, respectively. The lower limit of the load range is due to the minimum load recommended for a reciprocating engine-based generator set. Below this limit, the prime mover cannot keep the frequency stable and its efficiency is very low (Matelli et al., 2011).

$$\eta_m = -0{,}1112\,L^2 + 0{,}2674\,L + 0{,}2407 \tag{2}$$

$$\dot{m}_g = -2{,}387\,L^2 + 5{,}705\,L - 1{,}706 \tag{3}$$

$$T_g = 172\,L + 241 \tag{4}$$

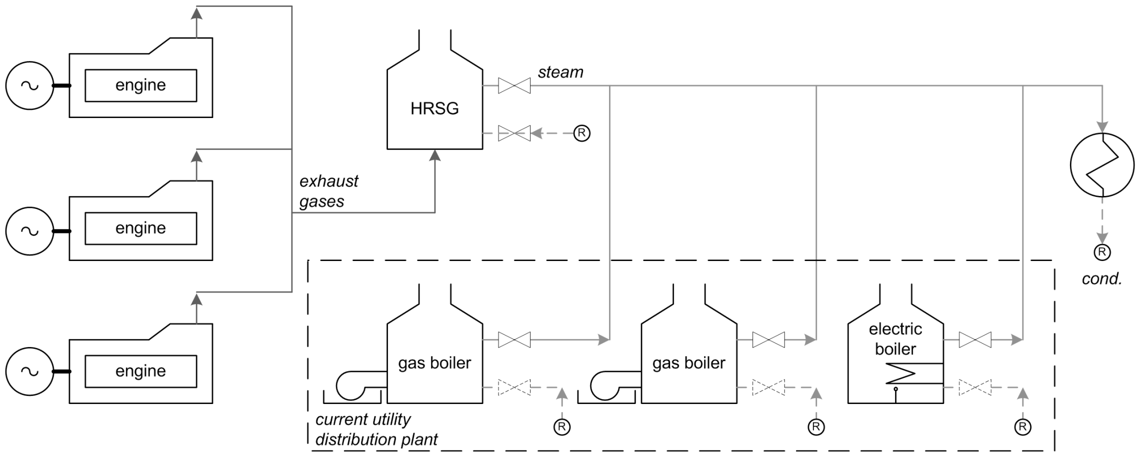


Figure 2. Proposed cogeneration plant.

In order to characterize the heat-match mode, the heat recovered from *N* prime movers operating at a load *L* must be equal to the steam demand at any time, according Eq. (5). The exhaust gases specific heat is considered constant and equal to 1,15 kJ/kgK.

$$\dot{Q}_s = N\,\{\,\dot{m}_g\,c_{p,g}\left(T_g - T_{st}\right)\} \tag{5}$$

At 7:00, the steam demand is maximum (Fig. 1), so that three engines in full load operation are required to meet such a demand. At other instants, both engine load *L* and the number of operating engines *N* can vary. The load and number of movers are calculated so that a pinch point of 20 °C is kept in any time. Pinch point is given in Eq. (6). The exhaust gases temperature at the pinch point is calculated through Eq. (7), which also gives the heat transferred in the HRSG evaporator section. The heat transferred in the HRSG economizer section is given in Eq. (8).

$$\Delta T_p = T_{g,p} - T_s \tag{6}$$

$$\dot{Q}_{ev} = N\,\{\,\dot{m}_g\,c_{p,g}\left(T_g - T_{g,p}\right) = \dot{m}_s\left(h_s - h_l\right)\} \tag{7}$$

$$\dot{Q}_{ec} = N\,\{\,\dot{m}_g\,c_{p,g}\left(T_{g,p} - T_{st}\right) = \dot{m}_s\left(h_l - h_c\right)\} \tag{8}$$

The power generated is calculated through Eq. (9). In this equation, the nominal power output of each generator set is equal to 2345 kW. The fuel consumed by the plant is calculated according Eq. (10). According São Paulo gas company, the fuel presents a lower heating value equal to 39348 kJ/m³ and a specific mass equal to 0,76 kg/m³. The overall plant efficiency is given in Eq. (11).

$$\dot{W} = \dot{W}_n\,NL \tag{9}$$

$$\dot{m}_f = \dot{W}\,\rho_f / \left(\eta LHV\right) \tag{10}$$

$$\eta_o = \rho_f\left(\dot{W} + \dot{Q}_s\right) / \left(\dot{m}_f\,LHV\right) \tag{11}$$

The set of equations previously presented composes the cogeneration plant model. The model is computationally implemented through the EES, a software based on the Newton-Raphson algorithm that also presents a powerful library of thermodynamic data for several substances. The model is solved for every hour of the day in order to determine the number of operating engines and their respective loads along the day. Other important parameters also calculated are the consumed fuel, the generated power, the overall efficiency and the exhaust gases temperature at the stack.

## 4. ECONOMIC MODEL

The economic model aims to quantify the profitability of the cogeneration plant investment when compared to the current energy costs of the automotive industry. It is expected the investment generates an annual revenue equal to the current expenses minus the cogeneration expenses, as shown in Tab. 1.

Table 1. Current and cogeneration expenses.

| Expenses | Current status (MR$/yr) | Cogenaration (MR$/yr) |
|---|---|---|
| Natural gas | 2,979 | 8,785 |
| Power | 32,696 | 24,479 |
| Generator set maintenance | – | 0,169 |
| Total | 35,675 | 33,433 |

The unitary costs used to calculate the expenses presented in Tab. 1 are presented as follows. Currently, the average power cost is 171,43 R$/MWh. The average power cost take into account peak and off-peak periods. The fuel monthly bill is composed of a fixed value of about 43 kR$ plus 0,94 R$ for each consumed cubic meter. When considering cogeneration, the gas company can offer a special price of 0,77 R$/m³ (see section 5.1). The generated power also represents an avoided power expense, but the generator set maintenance cost must be taken into account. The generator set manufacturer informs a maintenance value of 1,91 USD/MWh. Since the current utility plant should be kept for backup purposes, it is considered that the maintenance cost regarding the steam generators does not change significantly. From Tab. 1, a revenue of about 2,3 MR$/yr can be expected.

The total investment is about 5,7 MR$, estimated from the following figures:

- Generator set Waukesha 12V275GL+: 1,4 MR$ each;
- Heat recovery steam generator: 0,26 MR$;
- Building and mechanical/electrical assembly: 22% of the total invested

In general, the investment profitability is assessed through three interrelated parameters: discounted pay-back, Eq. (12); net present value, Eq. (13); and internal rate of return, Eq. (14).

$$DPB=-\frac{\ln\left(1-kI/R\right)}{\ln\left(1+k\right)} \tag{12}$$

$$NPV=R\frac{\left(1+k\right)^n-1}{k\left(1+k\right)^n} \tag{13}$$

$$R\frac{\left(1+IRR\right)^n-1}{k\left(1+IRR\right)^n}=0 \tag{14}$$

## 5. RESULTS

The simulation results are presented in Tab. 2. The plant fuel consumption is around 18100 m³/day; the generated electric energy is around 132 MWh/day; and the generated thermal energy in the form of saturated steam is around 78 MWh/day. Since the power output, the exhaust gases flow and the exhaust gases temperature depend on the engine load, the overall efficiency also depends on the load, hence varying along the day. The maximum overall efficiency is 0,6291 at 07:00; the minimum is 0,5936 at 11:00. The average daily efficiency is 0,6132. The load effect on the overall, power and thermal efficiencies is shown in Fig. 3.

Varying the number of operating engines proved to be a proper strategy for efficiency maximization. At 12:00, for instance, two engines with a load equal to 0,9435 meets the demands and the overall efficiency is 0,6284. If three engines were operating at this time, their load would be 0,6546 and the overall efficiency would be 0,5789.

The Brazilian natural gas companies can offer the fuel with a special price for cogeneration if the plant meets the criteria defined in the proper legislation (Brasil, 2006). The Brazilian Electricity Regulatory Agency (Aneel) stipulates that a plant can be legally qualified as a cogeneration plant if Eqs (15-16) are satisfied.

$$E_t \geqslant 0{,}15\, E_f \tag{15}$$

$$\frac{1}{E_f}\left(E_e + \frac{E_t}{X}\right) \geqslant F_c \tag{16}$$

$E_t$, $E_f$ and $E_e$ are readily calculated from Tab. 2; $F_c$ and $X$ depends on the plant nominal power and the fuel used and they are taken from Tab. 3. For the case presented in this work, $E_f$ = 125513 MWh/yr, $E_t$ = 28487 MWh/yr, $E_e$ = 48399 MWh/yr, $F_c$ = 1,86 and $X$ = 0,51. With such values, Eqs. (15-16) are both satisfied.

Table 2. Simulation results

| Hour | $\dot{m}_s$ (kg/s) | $\dot{Q}_s$ (kW) | $N$ (–) | $L$ (–) | $\dot{m}_g$ (kg/s) | $T_g$ (°C) | $T_{st}$ (°C) | $\dot{W}$ (kW) | $\dot{m}_f$ (kg/s) | $\eta_o$ (–) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1,139 | 2737 | 2 | 0,9435 | 4,964 | 403,3 | 163,9 | 4602 | 0,2256 | 0,6284 |
| 2 | 1,111 | 2671 | 2 | 0,9205 | 4,935 | 399,3 | 164,7 | 4495 | 0,2211 | 0,6259 |
| 3 | 1,083 | 2604 | 2 | 0,8975 | 4,903 | 395,4 | 165,5 | 4390 | 0,2168 | 0,6231 |
| 4 | 1,111 | 2671 | 2 | 0,9205 | 4,935 | 399,3 | 164,7 | 4495 | 0,2211 | 0,6259 |
| 5 | 1,111 | 2671 | 2 | 0,9205 | 4,935 | 399,3 | 164,7 | 4495 | 0,2211 | 0,6259 |
| 6 | 1,333 | 3205 | 3 | 0,7364 | 4,613 | 367,7 | 171,1 | 5511 | 0,2821 | 0,5967 |
| 7 | 1,722 | 4139 | 3 | 0,9512 | 4,973 | 404,6 | 163,6 | 6957 | 0,3407 | 0,6291 |
| 8 | 1,583 | 3806 | 3 | 0,8745 | 4,870 | 391,4 | 166,3 | 6428 | 0,3187 | 0,6201 |
| 9 | 1,556 | 3739 | 3 | 0,8592 | 4,846 | 388,8 | 166,8 | 6324 | 0,3145 | 0,6180 |
| 10 | 1,444 | 3472 | 3 | 0,7978 | 4,738 | 378,2 | 169,0 | 5915 | 0,2981 | 0,6082 |
| 11 | 1,306 | 3138 | 3 | 0,7211 | 4,579 | 365,0 | 171,6 | 5410 | 0,2781 | 0,5936 |
| 12 | 1,139 | 2737 | 2 | 0,9435 | 4,964 | 403,3 | 163,9 | 4602 | 0,2256 | 0,6284 |
| 13 | 1,417 | 3405 | 3 | 0,7824 | 4,708 | 375,6 | 169,5 | 5813 | 0,2940 | 0,6055 |
| 14 | 1,583 | 3806 | 3 | 0,8745 | 4,870 | 391,4 | 166,3 | 6428 | 0,3187 | 0,6201 |
| 15 | 1,389 | 3338 | 3 | 0,7671 | 4,678 | 372,9 | 170,0 | 5712 | 0,2900 | 0,6027 |
| 16 | 1,583 | 3806 | 3 | 0,8745 | 4,870 | 391,4 | 166,3 | 6428 | 0,3187 | 0,6201 |
| 17 | 1,417 | 3405 | 3 | 0,7824 | 4,708 | 375,6 | 169,5 | 5813 | 0,2940 | 0,6055 |
| 18 | 1,389 | 3338 | 3 | 0,7671 | 4,678 | 372,9 | 170,0 | 5712 | 0,2900 | 0,6027 |
| 19 | 1,389 | 3338 | 3 | 0,7671 | 4,678 | 372,9 | 170,0 | 5712 | 0,2900 | 0,6027 |
| 20 | 1,389 | 3338 | 3 | 0,7671 | 4,678 | 372,9 | 170,0 | 5712 | 0,2900 | 0,6027 |
| 21 | 1,167 | 2804 | 2 | 0,9666 | 4,990 | 407,3 | 163,1 | 4710 | 0,2302 | 0,6306 |
| 22 | 1,389 | 3338 | 3 | 0,7671 | 4,678 | 372,9 | 170,0 | 5712 | 0,2900 | 0,6027 |
| 23 | 1,389 | 3338 | 3 | 0,7671 | 4,678 | 372,9 | 170,0 | 5712 | 0,2900 | 0,6027 |
| 24 | 1,333 | 3205 | 3 | 0,7364 | 4,613 | 367,7 | 171,1 | 5511 | 0,2821 | 0,5967 |

Table 3. $F_c$ and $X$ factors (Brasil, 2006).

| Nominal power | Natural gas, coal and petroleum products | Other fuels |
|---|---|---|

| (MW) | $X$ | $F_c$ | $X$ | $F_c$ |
|---|---|---|---|---|
| $\dot{W}_n \geqslant 5$ | 2,00 | 0,47 | 2,50 | 0,32 |
| $5<\dot{W}_n \leqslant 20$ | 1,86 | 0,51 | 2,14 | 0,37 |
| $\dot{W}_n > 20$ | 1,74 | 0,54 | 1,88 | 0,42 |

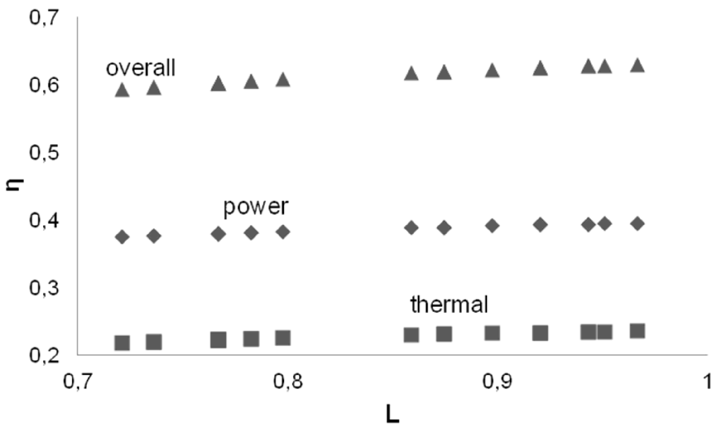


Figure 3. Load engines effect on the cogeneration plant efficiency.

The investment period is 25 years, which is the expected life of the generators set. The reference interest rate k is taken as the minimum profitability rate (MPR) of the automotive industry, which accepts any investment that presents MPR > 8%. For these parameters, the results from the preliminary economic analysis are DPB = 2,9 years, NPV = 44 MR$ and IRR = 35%.

Currently, the Central Bank of Brazil's Monetary Policy Committee (COPOM) is signaling a reduction in the benchmark interest rate. A sensitive analysis showing the effects of the interest rate rates on the economic analysis results is shown in Tab. 4. The lower the interest rate, the lower the DPB and the higher the NPV; on the other hand, the IRR is favored in a scenario with higher rates.

Table 4. Effect of the interest rate on the economic analysis.

| k (%) | DPB (years) | NPV (MR$) | IRR (%) |
|---|---|---|---|
| 5 | 2,71 | 46,7 | 34,5 |
| 6 | 2,76 | 45,8 | 34,7 |
| 7 | 2,81 | 44,9 | 34,9 |
| 8 | 2,87 | 44,0 | 35,2 |
| 9 | 2,93 | 43,2 | 35,4 |
| 10 | 2,99 | 42,3 | 35,7 |

## 5. CONCLUSION

In this work, a preliminary technical and economic study was carried out for a cogeneration plant application in an automotive industry located in São Paulo. Three 2435 kW generator sets based on reciprocating internal combustion engines are selected to generate power. The heat associated to the engines exhaust gases are recovered to generate steam. The number of operating engines are calculated in order to maximize the overall efficiency. The proposed cogeneration plant proved to be technically feasible, meeting the criteria established by the Brazilian Electricity Regulatory Agency (Aneel). Regarding the preliminary economic aspect, annual savings of about 2,3 MR$ are expected when compared to the current status (no cogeneration), resulting in an discounted payback of almost payback. At the end of the investment, a net present value of 44 MR$ and a internal rate of return equal to 35%.

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