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# Economic potential of natural gas-fired cogeneration in Brazil: two case studies

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**Abstract**

Recent restructuring of Brazil's power sector, allied to the expected larger share of natural gas in the nation's grid and the cost reductions of gas-fired power generation technologies, has introduced a set of situations apparently favorable to the expansion of natural gas-fired cogeneration. However, electricity self-generation applications are restricted to specific cases in Brazil. In order to deal with this issue, the COGEN model was developed to assess the economic potential of cogeneration ventures from the standpoint of the investor and guide incentive public policies. This model has been applied to two cases in Brazil — a chemical plant and a shopping mall — showing that the highest economic potential for gas-fired cogeneration in Brazil is found in industrial plants faced with high values of loss of load. In the commercial sector, measures reshaping the load curve of enterprises — such as cold storage — might be much more interesting than fired cogeneration. 

*Keywords:* Cogeneration in Brazil; Gas-fired technologies; Cogeneration model

Due to the ample availability and low costs of hydro-power, cogeneration is currently applicable only to very specific cases in Brazil, being concentrated in industrial plants that use waste materials to generate power, such as cane bagasse in the sugar and alcohol industry and black liquor in the pulp and paper segment [1]. Additionally,

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**Nomenclature**

| | |
|---|---|
| BF | backup factor |
| C | compressor |
| CC | combustion chamber |
| CCGT | combined cycle gas turbines |
| COP | performance coefficient of the refrigeration system |
| EE | electric output |
| $F_{exhaust}$ | exhaust mass flow |
| $F_{steam}$ | steam mass flow |
| GE | gas engines |
| GLA | gross leasable area |
| GT | gas turbines |
| H | enthalpy |
| HPGT | high performance gas turbines |
| HRSG | heat recovery steam generator |
| LP | low pressure steam |
| LPGT | low performance gas turbines |
| $M_{GN}$ | natural gas consumption |
| MP | medium pressure steam |
| $P$ | pressure |
| $P_{st}$ | steam turbine output power |
| $Q_{base}$ | heat base load |
| $Q_{max}$ | maximum heat load |
| SF | surplus factor |
| $T$ | temperature |
| TR | ton of refrigeration |
| TRA | total roofed area |
| UHRSG | unfired heat recovery steam generator |
| $\eta_{ST}$ | steam turbine efficiency |

cogeneration is currently facing barriers caused by an unfavorable institutional context [2]. Issues related to tariff levels for surplus power sales, back-up power contracts and transmission rates, among others, constitute some of the main stumbling-blocks hampering the development of cogeneration in Brazil.

However, recent restructuring of Brazil's power sector, together with legal and regulatory initiatives, have resulted in rising emphasis on the participation of private enterprise in power generation. The structural concept shaping Brazil's power sector is based on the introduction of competition in areas such as power generation and retailing. Furthermore, Brazil's electric power sector features a high risk of electricity shortfalls and is faced with a lack of funding for investment and expansion of power supplies.

This means that cogeneration — the technology for production of both electricity and heat from a single energy source — takes on increasing importance. Global efficiency rates for energy conversion through cogeneration systems are relatively high at 70 – 90%, outstripping the efficiency rates obtained from free-standing heat and power systems such as boilers and thermo-power plants. Thus, cogeneration technology is efficient in terms of energy and offers a decentralized power generation option for both industrial and commercial sectors. It reduces not only public investments in power generation, but also funding assigned to electricity transmission and distribution. Moreover, cogeneration can be implemented quite naturally at load centers where the problem of servicing the market is more acute. This is therefore a short-term option to expand the system through private enterprise, while reducing the risk of shortfalls in systems with low reserve margins.

Also, an analysis of Brazil's industrial plants indicates a considerable potential for power generation as a by-product of industrial production, which could result in better use of Brazil's primary energy sources from the thermodynamic standpoint. Additionally, once the Bolivia–Brazil Gas Pipeline starts up operations and expands its capacity to 30 million cubic meters per day by AD 2003, Brazil's natural gas supply will increase appreciably. Although part of this amount will be used by thermopower plants, it is also expected that the industrial and commercial sectors will show some interest in consuming natural gas, provided that incentives are offered. This increase in natural gas supplies is paralleled by lower fixed costs for gas-fired engines and turbines used in cogeneration plants, so making these investments even more attractive to private entrepreneurs eager to make good use of low sunk costs or short lead-times for return on investments.

In general terms, recent measures introduced to restructure Brazil's power sector, allied to the reshaping of its energy grid, assign a larger share to natural gas while reducing the costs of gas-fired power generation technologies, ushering in a set of factors that seem relatively favorable to the expansion of cogeneration. However, the current situation does not confirm these expectations. It still remains to be discovered whether there is any interest on the part of private investors, or the industrial/commercial sectors, in investing in cogeneration within the current context of the Brazilian economy. Government policies that could encourage such investments also need to be identified.

Faced with this situation, the COGEN model was developed. Its main objective is to assess the economic potential of cogeneration enterprises from the standpoint of the investor. The application of the COGEN model could thus help to identify measures fostering an expansion of cogeneration in Brazil, reducing existing barriers and paving the way for a context more favorable to its use and expansion.

## 1. COGEN model

The COGEN model has been developed for use in economic feasibility analyses of cogeneration plants powered by natural gas, set up by ventures in the commercial and industrial sectors. Through this model, economic assessments are carried out from the standpoint of the private investor, pinpointing barriers and incentives for possible future cogeneration ventures.

The model consists of four integrated modules, running on *Stella* software:

- COGEN 1: Gas turbines — commercial sector
- COGEN 2: Gas engines — commercial sector
- COGEN 3: Combined cycle gas turbine — industrial sector
- COGEN 4: Gas turbines — industrial sector

Users of this model should define the sector in question, in order to select one of the model modules (Fig. 1). There are three possible configurations for cogeneration plants, for each sector. For the commercial sector, the following configurations have been defined: open cycle with high-performance gas turbine (HPGT) with no additional fuel burned, and open cycle with low-performance turbine (LPGT) with additional fuel burned in a heat recovery steam generator — COGEN module 1; and Otto cycle with gas-fired alternative engines (GE) burning additional fuel in a heat recovery steam generator — COGEN module 2. The following configurations have been defined for the industrial sector: combined cycle with high-performance gas turbine and back-pressure steam-turbine without extraction (CCGT) — COGEN module 3; and the configuration based on the open cycle for high and low performance turbines (HPGT and LPGT) — COGEN module 4.

Each of these modules represents a different cogeneration technology to be assessed. The user should compare the results obtained (sizing and economic outcome) between the COGEN 1 and COGEN 2 modules for the commercial sector and the COGEN 3 and COGEN 4 modules for the industrial sector.

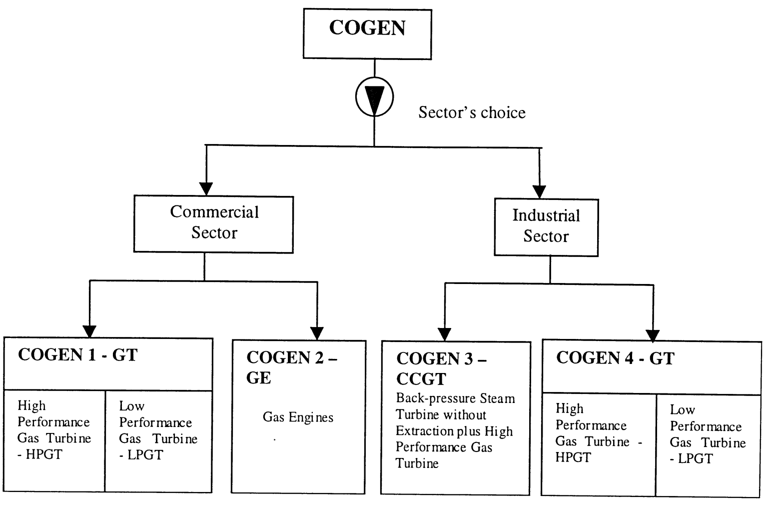


Fig. 1. COGEN model structure. Note: the commercial sector in Brazil lacks the scale required for combined cycles. The combined cycle adopted for the industrial sector in COGEN module 3 is the simplest version, in order to check the feasibility of this cycle when generating the minimum possible amount of surplus power. In the commercial sector, low enthalpy steam generation is considered, as well as power and an absorption refrigeration system; in the industrial sector, medium and high enthalpy steam generation is considered, in addition to power.

When drawing up the economic balance for cogeneration, the COGEN model gives the revenues and costs for each system assessed. Cogeneration revenues consist of: (1) electricity saved, not acquired from the network; (2) the sale of possible surplus generation to the network; (3) the impacts avoided of a possible shortage of power supplies, which is only entered in the accounts should the entrepreneur be averse to risks. In the case of the commercial sector, this involves the fixed and variable costs of a diesel-fired generator which runs during power outages. In the case of the industrial sector, this involves a loss in revenues which is avoided after the installation of a cogeneration plant, so completely eliminating the risk of any power shortages for the user [3].

The costs consist of: (1) the purchased electricity from an utility to cover the system's down-time and supplementary electric demand if the cogeneration unit does not supply all the electric demand of the enterprise; (2) investments and maintenance of the cogeneration system;[1] (3) investment in heat recovery steam generators and accessories for the cogeneration system; (4) engineering and installation costs of the cogeneration equipment; (5) balance of expenditures on fuel, taking into consideration the cogeneration plant and the original process.

With the COGEN model, the selection criteria for cogeneration ventures is the internal rate of return, which should exceed a basic figure established by the user of the model.

The COGEN model has two basic applications:

- Horizontal application: survey of the technical and economic potential of cogeneration for a specific economic segment: chemical industry, shopping center, etc.[2] In this case, the user undertakes a bottom-up analysis, assessing the attractiveness of each venture separately and then aggregating the results for the segment as a whole. The COGEN model is used for each venture, allowing definition on a case-by-case basis of the cogeneration system that is most feasible in economic terms, according to the pre-defined entry variables.
- Vertical application: a single venture is assessed individually, in order to identify barriers to the introduction of cogeneration facilities at specific industrial plants and commercial enterprises. In this case, the COGEN model is used for sensitivity analyses. This is the manner in which it is used in this article: in an assessment for a shopping center in Rio de Janeiro, and a specific chemical plant in Brazil.[3]

The description of each COGEN model module is given below.

[1] In some cases, this amount may correspond to an investment balance, meaning that the entrepreneur decides to invest in a cogeneration system instead of acquiring other steam or refrigeration equipment [4].

[2] Technical potential represents the cogeneration potential, considering only the mass and energy balances required facing all technological alternatives available on the Brazilian market. The economic potential of cogeneration is the share of technical potential which is economically feasible.

[3] A project currently under way at the Energy Program Department of the Rio de Janeiro Federal University is identifying the economic and technical potential of cogeneration at malls throughout Rio de Janeiro, based on the COGEN model [1].

### *1.1. COGEN 1 and COGEN 4 — gas turbine modules*

The COGEN 1 (commercial sector) and COGEN 4 (industrial sector) modules, based on gas turbines, differ on only two points: (1) under COGEN 1, in contrast to COGEN 4, the steam produced by the cogeneration plant is used in an absorption refrigeration system for air-conditioning purpose (thus, COGEN 1 includes both a cogeneration plant and an absorption cooling system that uses a lithium–bromide solution in the absorber); (2) under the COGEN 1 module, the effects of a shortfall in power supplies are entered in the accounts according to a methodology proposed for the commercial sector, determining the fixed and variable costs of a diesel-fired generator operating during power outages. The COGEN 4 module follows the methodology, proposed for the industrial sector, estimating impacts on the basis of loss of revenues for an industrial plant caused by an interruption in power supplies.

Despite these differences, the economic assessment and sizing of the cogeneration systems under the COGEN 1 and COGEN 4 modules are similar, working on the hypothesis that the system should be sized to meet the process heat needs of the user. Thus, the user of the model should characterize the heat demands of the venture properly [5].

Depending on variations in heat demand over the period, cogeneration systems may or may not need to burn supplementary fuel in heat recovery steam generators in order to boost the availability of the usable heat of the plant. Under the COGEN 1 and COGEN 4 modules, two cogeneration systems are outlined, based on gas turbines:

- System based on HPGT. Under this system, there is no supplementary fuel burned in the heat recovery steam generator: the peak heat load demand of the venture is met by the exhaust gases produced by the gas turbine.
- System based on LPGT (Fig. 2). Under this system, the gas turbine meets the heat load for the bottom of the heat load curve (Fig. 3), with the remainder supplied by the heat recovery steam generator burning additional fuel.

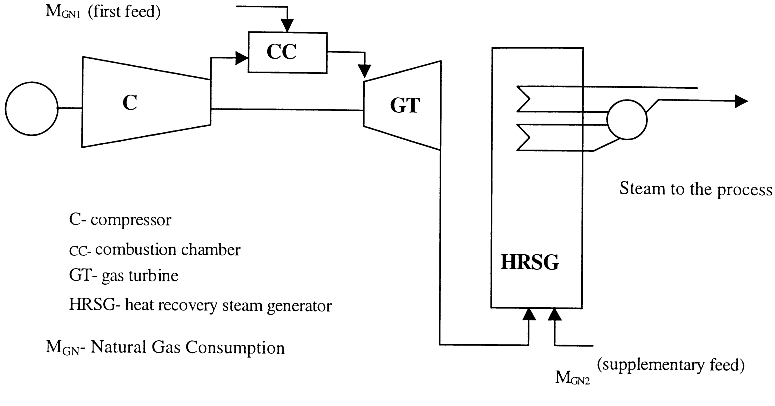


Fig. 2. Schematic outline of the cogeneration system using LPGT. Note: the system based on HPGT differs from that shown here only through the fact that no additional gas is consumed, with exchangers being used instead of boilers to obtain the steam required by the process.

The COGEN 1 and COGEN 4 modules run on a data-base of 60 gas turbines with power ranging from 0.5 to 30 MWe. This data-base includes the capital cost of the turbines (US$/kW), the rated power (kW), the heat rate (kJ/kWh), the mass outflow of exhaust gas (kg/s) and the corresponding temperature of this gas (°C). Based on this data-base, the modules establish the capital cost curves×rated power, and rated power×rated efficiency. The ratio between the usable heat produced by the turbine and its rated power is also expressed in curves established on the basis of the energy balance for each piece of equipment. The amount of usable heat available in the escape gases of the turbine represents some 67% of the total initial energy, with some 78% of this being effectively usable [6].

Based on the heat load curve for the process in which the cogeneration plant will be installed, the rated power and rated efficiency of the gas turbines used are obtained for the two systems described above. The data-base for the modules contains power and efficiency correction curves for gas temperatures and pressures at the input point of the Brayton Cycle combustion chamber, which differ from the conditions used to establish the rated parameters for the turbines. Thus, both the rated and effective operating values are obtained for the equipment.

Having sized the system, the module then calculates its economic balance, determining the portion relative to the costs and revenues of the system under assessment, so identifying the internal rate of return of the venture.

### *1.2. Module 2 — COGEN 2 — gas engine model*

The module sizes cogeneration systems based on alternative gas-fired engines (Fig. 4). These systems basically consist of an engine associated with an electric alternator, a heat recovery steam generator.

This system is similar to that of the LPGT with a difference that the basic equipment used here is a gas-fired engine whose energy balance differs from that of the turbine, assigning a higher priority to power generation rather than producing usable heat. The average power generation efficiency of the engines available on the Brazilian market corresponds to 40%, while the usable heat at the engine outlet is divided into two parts: the first corresponds to the amount of heat made available by

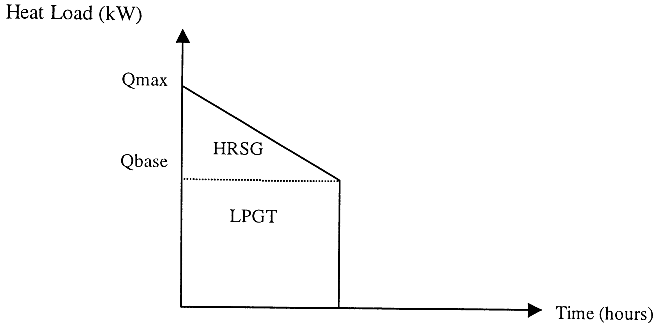


Fig. 3. Example of heat load curve applied to the LPGT system. Note: $Q_{max}$: maximum heat load; $Q_{base}$: basic head load; LPGT: system based on low performance gas turbines; HRSG: heat recovery steam generator.

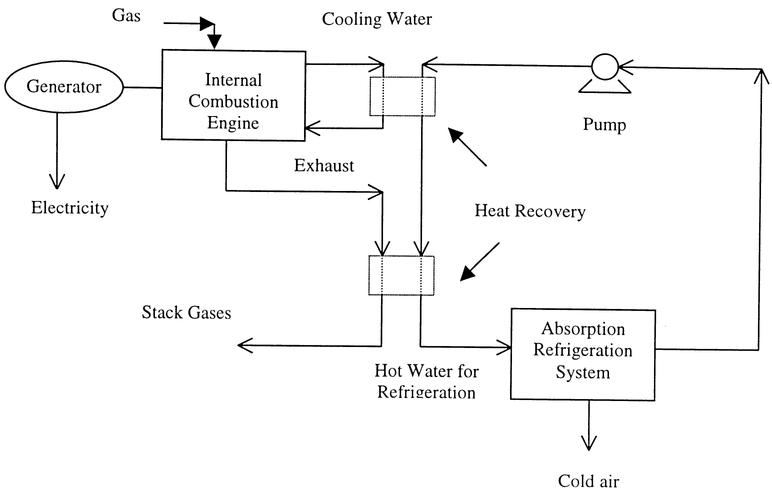


Fig. 4. Schematic outline of a gas-fired engine cogeneration plant.

the exhaust, equivalent to 22% of the total energy at the engine uptake point, while the second corresponds to the amount available in the cooling water, equivalent to 16% of the total energy at the engine uptake point [6]. Due to its low enthalpy, the available heat requires the introduction of a heat recovery steam generator burning additional fuel in order to meet the maximum heat load demands on the cogeneration system.

Sizing the cogeneration unit, under the COGEN 2 module, basically follows the same procedure as that adopted to the COGEN 1 module for the LPGT system, with the basic heat demand in this module met by the engine rather than by the low performance gas turbine. The remaining heat demand is met by burning additional fuel in a recovery steam generator. As the gas-fired engines were designed for small and medium capacities, with rated power varying between 0 and 5 MW in the COGEN 2 data-base, this system is suitable only for the commercial sector. Similar to the COGEN 1 module, it includes the sizing of the absorption cooling system, which can be linked to the cogeneration generation plant.

### *1.3. Module 3 — COGEN 3 — CCGT model*

The COGEN 3 module covers the combined operations of a back-pressure steam turbine with no extraction and a HPGT, as shown in Fig. 5.

In Fig. 5, condition 3 — heat recovery steam generator water inlet — is defined by the user, as well as the steam patterns required by the process, condition 1. Condition 2 — steam turbine inlet — is determined through an iterative procedure. In this procedure, the user of the model should define the operating pressure of the steam turbine according to the turbines available on the market,[4] and stipulate the exhaust

[4] Pressures varying between 1 and 6 MPa.

temperature and exhaust outflow (condition 4), that will be used in the first step of the iterative procedure. Having the user stipulate these variables, the model determines the temperature of the steam produced by the heat recovery steam generator through the heat recovery steam generator curves (see Fig. 6). The COGEN 3 data-base has exhaust temperature curves between 400 and 600°C, with exhaust outflows between 8 and 32 kg/s. In these curves, the ordinate is given as the ratio between the flow of steam produced in the boiler (kg/h), $F_{\text{steam}}$, and the exhaust outflow generated by the gas turbine (kg/s), $F_{\text{exhaust}}$. The abscissa gives the pressure of the steam produced in the heat recovery steam generator.

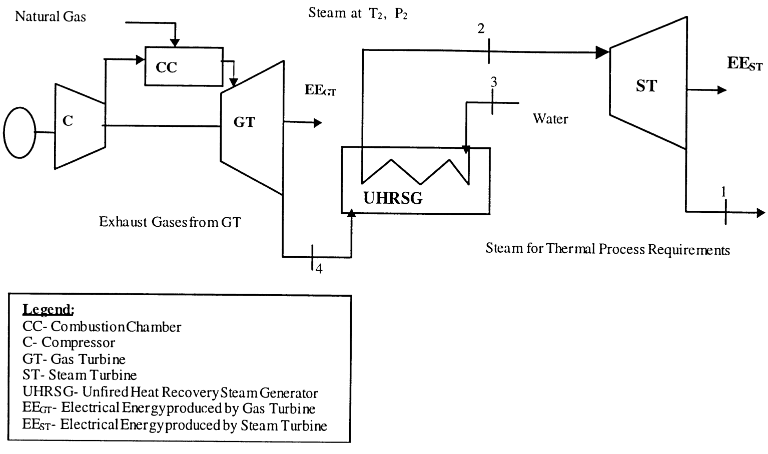


Fig. 5. Combined cycle gas turbine (CCGT) — simplified scheme for industrial cogeneration.

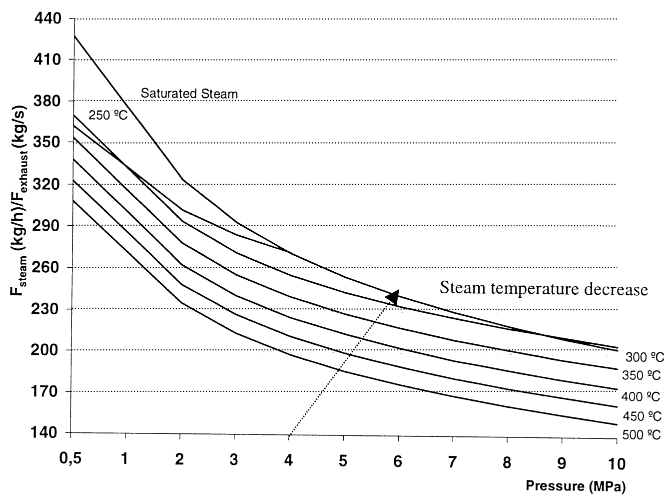


Fig. 6. Specific exhaust steam outflow rate at 400°C.

It is assumed that the temperature of the steam produced by the heat recovery steam generator is the same as the inlet temperature of the steam turbine.[5] With this temperature and the steam pressure at the steam turbine's inlet point, the model gives the enthalpy for condition 2 from its data-base (Mollier Diagram), and also establishes the useful heat that the gas turbine should supply at its outlet for the heat recovery steam generator — condition 4. Based on the usable heat demands on the gas turbine and the curve for the rated power×usable heat for this turbine, its rated power is obtained. The COGEN 3 module has a data-base which includes all 60 gas turbines available on the Brazilian market, relating their rated power to the turbine exhaust outlet conditions (temperature and flow). Through the rated power of the gas turbine, the new exhaust outflow and temperature figures are established for use by the model in its iterative box through to convergence, determining the steam turbine inlet temperature and consequently the condition 2 enthalpy.

After convergence, the COGEN 3 module sizes the steam turbine operation power through the expression above, and also sizes the rated and effective power of the gas turbine as described in the COGEN 4 module. Finally, the module gives the economic balance for the system.

$$P_{\mathrm{ST}} = (H_2 - H_1)/\eta_{\mathrm{ST}} \tag{1}$$

where

$P_{\mathrm{ST}}$ is the steam turbine's output power;
$H_2$ is the steam enthalpy at the steam turbine's inlet point;
$H_1$ is the steam enthalpy required in the process;
$\eta_{\mathrm{ST}}$ is the steam turbine's efficiency.

## 2. Case studies

The COGEN model was applied to two specific enterprises: a chemical plant in Southeast Brazil, and the Rio Sul Shopping Center in Rio de Janeiro. The selection criteria for the cogeneration systems assessed consisted of the internal rates of return on investment. In the assessment undertaken, in order for a specific system to be considered as economically feasible, its internal rate of return had to top the highest rate of return found on the Brazilian market for investments that did not involve appreciable risks, or for fixed income investments. The upper limit for these investment rates on the Brazilian market is the Interbank Certificate of Deposit (ICD), whose forecast yield for 1999 was 25.0%.[6] The figure of 25.0% adopted in this work

[5] There may be a slight drop in this temperature; however, this does cause a distortion of the results by more than 5%.

[6] In fact, the final figure for 1999 reached 15% in real terms (almost half the yield in 1998 at 31%). In this sense, our simulation results are very conservative.

is related to the economic situation in Brazil, and thus represents the minimum remuneration that a private investor would expect to obtain on invested capital in the current economic context. This is a relatively high rate compared to the figure of 15.0% p.a. traditionally used by Eletrobrás[7] in its planning [7], and is a specific result for the Brazilian context, as in more stable economies the internal rate of return ensuring the feasibility of investments is generally below 25.0%. However, although this figure may drop over the next few years, it is also expected that private investors will use a certain amount of prudence for short-term investments, particularly with regard to activities other than their core businesses, such as power generation at industrial plants or malls.

### *2.1. Chemical plant*

At the Brazilian chemical plant, heat demands are met by consuming BTE-type fuel oil purchased at a price of US$ 100/ton in stationary water-tube boilers, with an average steam generation efficiency rating of 80%.[8] The installation cost of the boiler and its ancillary equipment has already been amortized. The heat load factor — i.e. ratio between the average heat load demand and maximum heat load required — is equivalent to 0.88. Table 1 summarizes the energy demands of the plant [8].

The chemical plant has a high electricity load factor of 0.9, working with three shifts around the clock, and peaking for 6 h during the 24-h period. Specific power consumption by this plant corresponds to 70 kWh/ton, with the average unit value of its output at US$ 21/ton, consisting of an intermediate product for goods with a higher added value. In the base case simulation, the risk of a shortfall is not taken into consideration in the cogeneration economic balance. The power-to-heat ratio for the plant, which relates its power demand to its heat demand, is equivalent to 0.34, so indicating a higher demand for heat power than electricity. The annual average temperature, in the district where the plant is located, is 25°C at sea level.

#### *2.1.1. Application of the COGEN model to the chemical plant*

The results of the COGEN model for the base case under the current regulatory and rates context showed no economic feasibility for the three cogeneration systems

Table 1
Energy parameters for a Brazilian chemical plant

| | | |
|---|---|---|
| Electromechanical demand (GWh/year) | | 29.7 |
| Steam demand ($10^6$ kg/year) | MP[a] | 105 |
| | LP[b] | 6.2 |

[a] MP, saturated steam at medium pressure (1.8 MPa and 205°C).
[b] LP, superheated steam at low pressure (0.6 MPa and 180°C).

[7] Eletrobrás is the federally-owned holding company that, until 1995, controlled 90% of electricity generation activities in Brazil.
[8] The exchange rate used was 1 US$ = 1.90 R$, where R$ is the symbol for the Brazilian currency, Real.

assessed (Table 2). Nevertheless, the first two systems — HPGT and LPGT — were technically more adequate for the chemical plant under study than the CCGT system, whose immense generation of surplus power is due to the high heat demand of the chemical plant, compared to its electricity demand.[9] As the sizing of the cogeneration units is initially intended to meet heat demand, the generation of surpluses by this latter system is almost four times higher than the power demands of the plant.

There are three basic incentive policies for cogeneration that could be applied together or separately in the Brazilian context. The first one focuses on the power rates (the power purchase tariff, the buyback rate and the backup rate), through either higher prices or guaranteed purchase of cogenerated surplus power; the second centers on the gas rates, which represent an appreciable portion of the variable costs of the plant; and finally, the third targets equipment through government subsidies underwriting purchases. In this article, only the first two were studied.

The simulation of the stand-alone cogeneration incentive policy based on the power rates, did not produce satisfactory results, maintaining unaltered the current power purchase tariff, even when a legal obligation of buying the surplus power produced by the cogeneration system is imposed to the utility (Table 3). Therefore, we may say that the current low power purchase tariffs applied to the Brazilian industrial sector, are a strong barrier for investments on cogeneration systems.

Table 2
Chemical plant — base case

| | HPGT | LPGT | CCGT |
|---|---|---|---|
| *Tariff context* | | | |
| Electricity rate (US$/MWh) | 28.3 | 28.3 | 28.3 |
| Buyback Rate (US$/MWh) | 0.0 | 0.0 | 0.0 |
| Back-up purchase rate (US$/MWh) | 84.8 | 84.8 | 84.8 |
| Natural gas rate (US$/MMBTU) | 2.7 | 2.7 | 2.7 |
| *Results* | | | |
| Internal rate of return (% p.a.) | ≅0 | ≅0 | ≅0 |
| Capital cost — cogeneration unit (US$/kW) | 482.5 | 457.2 | 1000.0 |
| Rated power — gas turbine (MW) | 9.4 | 5.0 | 14.5 |
| Rated power — steam turbine (MW) | 0.0 | 0.0 | 2.2 |
| System availability (%) | 96.4 | 96.4 | 96.4 |
| Cogeneration efficiency (%) | 78.7 | 74.1 | 60.4 |
| Electricity generation (GWh/year) | 54.7 | 36.0 | 112.1 |
| Supply level[a] | 1.8 | 1.2 | 3.8 |
| Gas consumption ($10^6$ $m^3$/year) | 15.4 | 13.5 | 26.2 |
| Exhaust temperature (°C)[b] | 464 | 443 | 600 |
| Exhaust outflow (kg/s)[c] | 39.2 | 18.5 | 32.0 |

[a] Ratio between electricity produced and electricity demand.
[b] Initial estimate for iterative calculation of COGEN 3 equivalent to 443°C.
[c] Initial estimate for iterative calculation of COGEN 3 equivalent to 18.5 kg/s.

[9] For the combined cycle steam turbine, the inlet pressure of 4.0 MPa was taken, which is a figure commonly used in the industrial sector [9].

When maintaining all the initial parameters for the base case unaltered and doubling the utility purchase tariff, the system that seems most promising is the LPGT, which operates with the lowest gas consumption and supply levels. The internal rate of return of this system for a power purchase tariff of US$ 56.6/MWh varies between 24.0 and 30.5% p.a., almost underpinning its feasibility within a favorable context for selling off surplus electricity. By burning additional fuel in the heat recovery steam generator, the LPGT system is more flexible than the others, being better adapted to the heat and power demands of the chemical plant. The CCGT system proved completely inadequate for the case under study. The result also proved the positive impact of the buyback rate on the economic feasibility of the systems assessed.

Additionally, it is important to notice that the cogeneration system choice depends not only on the technical characteristics of each system assessed, but also on the energy demands of the industrial plant under analysis.[10]

By varying the gas tariff and maintaining the other parameters constant in relation to the base case, the best economic performance was found for the LPGT (Table 4). However, it was noted that merely reducing the gas tariff did not ensure the feasibility of this system in view of the pre-established criteria, although its internal rate of return for tariffs below US$1.8/MMBTU already proved more attractive.

Table 3
Sensitivity analysis — variation in power tariff — chemical plant

| Increase in base case electricity rate (%) | Internal rate of return (% p.a.) | | | | | |
|---|---|---|---|---|---|---|
| | SF:[a] 0.5 BF:[b] 1 | SF: 0.5 BF: 2 | SF: 0.75 BF: 1 | SF: 0.75 BF: 2 | SF: 1.0 BF: 1 | SF: 1.0 BF: 2 |
| *HPGT system* | | | | | | |
| 0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.2 | 4.4 |
| 100 | 20.0 | 19.0 | 24.6 | 23.5 | 29.0 | 28.0 |
| *LPGT system* | | | | | | |
| 0 | 0.0 | 0.0 | 2.5 | 1.0 | 4.4 | 3.1 |
| 100 | 26.5 | 24.0 | 28.2 | 27.2 | 30.5 | 27.8 |
| *CCGT system* | | | | | | |
| 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 100 | 1.4 | 1.0 | 8.3 | 8.0 | 13.5 | 13.4 |

[a] SF (surplus factor): ratio between the buyback tariff and the power purchase tariff.
[b] BF (back-up factor): ratio between the back-up purchase tariff and the power purchase tariff.

[10] Just for analysis, we simulated our chemical plant with a heat demand two times lower. In this case, the performance of the CCGT system became more attractive. Adopting a surplus factor of 0.5 and a backup factor of 1.0, the internal rate of return was 7.8% p.a., with a total rated power of 6.7 MW (5.7 MW for the gas turbine and 1.0 MW for the steam turbine).

Should risk reduction be considered in the cogeneration economic balance, even for base case conditions — i.e. for the current regulatory and tariff context — possible revenue losses avoided by installing a cogeneration plant underpin the feasibility of the HPGT and LPGT systems (Table 5) for the current loss of load probability of 9.0% [7]. Even with a drop in the current loss of load probability to 7.0%, the LPGT system still proved feasible. Thus, as the loss of load probability is directly related to the expansion of the power system generation park, any delay in this expansion could ensure the feasibility of cogeneration facilities at industrial plants. In fact, due to the current high risk of shortage of the Brazilian electric system, cogeneration is a promising alternative for the industrial sector, particularly for plants producing high added-value goods with a relatively high electric consumption.

### *2.2. Rio Sul Shopping Center*

Located in the city of Rio de Janeiro, the Rio Sul Shopping Center is a relatively large-scale venture with a considerable gross leasable area (GLA) (sum of the areas leased to its tenants) and total roofed area, TRA (Table 6). With regard to power consumption, it needs low quality heat (requirements do not exceed temperatures of around 200°C) for sanitary purposes and cooking food, while its electricity is used largely for lighting and air-conditioning purposes. The share held by the air-conditioning end-use in the power consumption of this mall is equivalent to 45.5% [10], which is higher than the Brazilian average of 34.0% [11]. The compressors account for 70% of the air-conditioning system electric consumption [12].

Table 4
Sensitivity analysis — variation in gas tariff — chemical plant[a]

| | Internal rate of return (% p.a.) | | |
|---|---|---|---|
| Gas tariff (US$/MMBTU) | HPGT | LPGT | CCGT |
| 1.6 | 1.4 | 14.6 | 0.0 |
| 1.8 | 0.0 | 11.5 | 0.0 |
| 2.0 | 0.0 | 8.4 | 0.0 |
| 2.2 | 0.0 | 4.6 | 0.0 |
| 2.6 | 0.0 | 0.0 | 0.0 |

[a] The city-gate gas tariff for the Bolivian gas is expected to achieve US$ 2.26/MMBTU; for the domestic gas produced in Rio de Janeiro the gas tariff will be US$ 1.84/MMBTU.

Table 5
Sensitivity analysis — power shortfall risk accounting — chemical plant

| | Internal rate of return (% p.a.) | | |
|---|---|---|---|
| Loss of load probability (%) | HPGT | LPGT | CCGT |
| 9.0 | 25.0 | 41.0 | 0.0 |
| 7.0 | 9.6 | 25.0 | 0.0 |

Table 6
Relative indicators: Rio Sul Shopping Center

| GLA[a] ($m^2$) | TRA[b] ($m^2$) | Specific monthly consumption ($kWh/m^2$) | | Electricity consumption[c] |
|---|---|---|---|---|
| | | by GLA | by TRA | (kWh/year) |
| 48,107 | 248,000 | 39.2 | 7.6 | 23,284.8 |

[a] Gross leasable area.
[b] Total roofed area.
[c] Estimated for 1998.

The air-conditioning system in this mall runs on a cooling system based on centrifugal compressors that use water-tanks to stockpile heat energy. This mall does not have an ice-bank; its power consumption is concentrated during the day, peaking at 7:00 p.m. The hottest day of the year occurs in summer-time, with the highest occupation rate for this mall noted on weekends. The power load factor on this day equals 0.53.

With regard to heat demand, the cogeneration plant to be installed should meet only the steam demand of the absorption refrigeration system, which remains in operation for 17 h, from 8:00 a.m. through to 01:00 a.m. Heat removal occurs largely between 11:00 a.m. and 07:00 p.m. peaking at 04:00 p.m. The cooling load factor is equals 0.67, taking into account only the operating hours of the mall, dropping to 0.45 on a 24-h basis [13].

With regard to the compression and absorption refrigeration systems, the figure of 120°C was adopted for the temperature of the absorption cycle steam generator; the figure of 5°C was adopted for the cold reservoir; the room temperature is defined for the hottest month of the year and at the hottest time of this month; from 1994 to 1996, the maximum daily temperatures for the hottest month in Rio de Janeiro reached 40°C. The efficiencies of the compression and absorption cooling systems are taken as 60% [14].

### *2.2.1. Application of the COGEN model — Rio Sul Shopping Center*

The application of the COGEN model to the base case, which corresponds to the current regulatory and tariff context in Brazil, demonstrated the lack of economic feasibility of the three cogeneration systems assessed. For the two cogeneration systems — HPGT and GE — surplus power generation was noted which could be marketed, provided that a sales tariff was duly established for these surpluses. The LPTG system operated without generating power surpluses (Table 7).

The application of the COGEN model to the case where the base case electricity rate doubles showed positive effects in the internal rate of return by increasing the buyback rate, and negative effects by increasing the back-up purchase tariff (Table 8). The HPGT and GE systems performed better than the LPGT system because they operated with higher supply levels, guaranteeing better revenues in the case of selling off surplus power, with lower investments per kWh generated. However, the internal rates of return, even when the utility purchase tariff increased by 100%, still

Table 7
Rio Sul Shopping Center — base case

| | HPGT | LPGT | GE |
|---|---|---|---|
| *Tariff context* | | | |
| Power tariff (US$/MWh) | 52.1 | 52.1 | 52.1 |
| Buyback rate (US$/MWh) | 0 | 0 | 0 |
| Back-up purchase tariff (US$/MWh) | 156.3 | 156.3 | 156.3 |
| Natural gas tariff (US$/MMBTU) | 3.9 | 3.9 | 3.9 |
| *Results* | | | |
| Annual internal rate of return (%) | ≅0 | ≅0 | ≅0 |
| Capital cost — cogeneration unit (US$/kW) | 487.2 | 514.0 | 640.0 |
| Capital cost — absorption chiller (US$/TR) | 1360 | 1360 | 1360 |
| Maximum heat load — air-conditioning (TR) | 2992 | 2992 | 2992 |
| $COP_{compression}$ [a] | 4.77 | 4.77 | 477 |
| $COP_{absorption}$ [a] | 0.99 | 0.99 | 0.99 |
| Rates power (MW) | 8.2 | 3.4 | 4.8 |
| Power generation (MWh/year) | 38.990 | 16.225 | 27.563 |
| Supply level [b] | 2.5 | 1.0 | 1.7 |
| Annual natural gas consumption ($10^6$ $m^3$) | 12.81 | 7.37 | 9.27 |

[a] COP, performance coefficient of the cooling system is defined as the ratio between the heat removal level obtained — usually measured in refrigeration tons (TR) — and the work required for this purpose.
[b] Supply level is the ratio between the power supply generated by the cogeneration system and the power demands of the mall after the installation of the cogeneration plant.

Table 8
Sensitivity analysis — variation in power tariffs — Rio Sul Shopping Center

| Increase in base case electricity rate (%) | Internal rate of return (% p.a.) | | | | | |
|---|---|---|---|---|---|---|
| | SF[a]: 0.5 BF[b]: 1 | SF: 0.5 BF: 2 | SF: 0.75 BF: 1 | SF:0.75 BF: 2 | SF: 1.0 BF: 1 | SF: 1.0 BF: 2 |
| *HPGT system* | | | | | | |
| 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 100 | 6.3 | 5.1 | 15.9 | 14.8 | 23.5 | 22.7 |
| *LPGT system* | | | | | | |
| 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 100 | 5.9 | 3.7 | 6.1 | 4.0 | 6.4 | 4.4 |
| *GE system* | | | | | | |
| 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 100 | 7.3 | 6.0 | 12.9 | 11.6 | 17.8 | 16.0 |

[a] SF (surplus factor): ratio between the power surplus sale tariff (buyback rate) and the power purchase tariff.
[b] BF (back-up factor): ratio between the back-up purchase tariff and the power purchase tariff.

remained below the minimum threshold established for the Brazilian case. Thus, it was not possible to ensure the feasibility of gas-fired cogeneration for this mall merely through tariff increases and a favorable context for the sale of surplus power and back-up purchase.

In turn, the reduction in the gas tariff currently charged to commercial consumers, while maintaining the other parameters constant in relation to the base case, failed to ensure the feasibility of the cogeneration system. The economic performance of the HPGT and GE systems did not alter, while the LPGT system reached the annual rate of return of 4.0% p.a., for the gas tariff of US$1/MMBTU. This is not an encouraging result, showing that, for the Rio Sul Shopping Center case, gas-fired cogeneration systems cannot be promoted only by gas tariff reductions. Nevertheless, by reducing the gas tariff to US$ 2.0/MMBTU within an increase of 100% in the utility purchase tariff, a higher internal rate of return was obtained for the LPGT system and the GE system (Table 9). Thus, for these systems, the joint effects of the gas and power tariffs could improve their economic performance.

We also simulated a mall installing an ice-bank and a cogeneration plant to implement a cold-storage air conditioning system. This reduced the maximum cooling load by 80%. The absorption cooling system operated with a capacity factor of 98%, and the power load factor of the mall rose to 0.70.[11] The results obtained for the tariff context most favorable to cogeneration showed that the cold-storage system shifted peak power consumption to periods with lower consumption rates and reduced the power tariff — or the revenues from the cogeneration system — which undermined the feasibility of the systems assessed.

Finally, in the last sensitivity analysis carried out, the inclusion of a reduction in the shortfall risk in the cogeneration economic balance failed to ensure the feasibility of the systems assessed, with only a slight improvement in the economic performance of the HPGT system, whose internal rate of return rose from 0% p.a. (base case) to 3.5% p.a. The loss of load probability for the South/Southeast/Mid-West

Table 9
Sensitivity analysis — variation in gas tariff and power purchased tariff — Rio Sul Shopping Center[a]

| | Internal rate of return (% p.a.) | | |
|---|---|---|---|
| | HPGT | LPGT | GE |
| *Gas tariff 2.0 US$/MMBTU* | | | |
| *Power purchased tariff (US$/MWh)* | | | |
| 52.1 | 0.0 | 0.0 | 0.0 |
| 104.2 | 0.0 | 16.4 | 11.0 |
| *Gas tariff 3.9 US$/MMBTU* | | | |
| *Power purchased tariff (US$/MWh)* | | | |
| 52.1 | 0.0 | 0.0 | 0.0 |
| 104.2 | 0.0 | 2.2 | 0.0 |

[a] Buyback rate = US$ 0/MWh and back-up rate = US$ 156.3/MWh.

[11] The Nova América Shopping Center in Rio de Janeiro has a cold-storage system and operated in 1998 with an average power load factor of 0.74 [15].

Interconnected System that supplies the city of Rio de Janeiro is currently at 9.0%. The installation of the cogeneration plant reduces this probability to zero at the Rio Sul Shopping Center.

## 3. Final remarks

The application of the COGEN model for the two case studies proposed proved the capability of the model developed to assess and identify the technical and economic potential of gas-fired cogeneration systems designed for ventures in the industrial and commercial sectors. The data-base for the model is restricted to 60 turbines and 12 engines, but can naturally be expanded and modified by the user, according to the region or country where the feasibility studies are carried out for gas-fired cogeneration systems. In terms of the results, it was noted that, although this decentralized power generation option, funded by private investment, is efficient in energy terms, the introduction of cogeneration facilities in Brazil is hampered by various obstacles. The main stumbling-blocks are linked to the current lack of definition for the regulator and tariff contexts. Although technically feasible for the mall, cogeneration proved feasible only within a reasonably favorable tariff context, and underpinned by combined incentive policies for this energy alternative. On the other hand, investments in a cold-storage system blocked the feasibility of cogeneration within any tariff context, indicating that there are demand-side energy efficiency gains in Brazil's commercial sector which proved more adequate than cogeneration, at least initially. In the case of the chemical plant, the economic feasibility of the cogeneration systems was largely related to the high risk of shortfalls in Brazil's power system. In this case, investments in cogeneration were mainly designed to minimize the risk of an interruption in power supplies to the chemical plant. A reduction in the natural gas tariff would also enhance the economic performance of the systems assessed.

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