# ENVIRONMENTAL AND FINANCIAL IMPACT ASSESSMENT OF NATURAL GAS COGENERATION PLANTS IN THE INDUSTRIAL SECTOR

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## ABSTRACT

This paper presents a case study on the impact of the use of natural gas cogeneration plants in industrial facilities from food companies established in the State of São Paulo, aiming at the financial and greenhouse gases emissions (GHG) analysis. It is proposed a comparison between two different energy supply models for two manufacturing plants, the first one based on electricity supply from local grid and steam from natural gas fired steam generators, and a second model that considers the industries energy needs being partially supplied through natural gas cogeneration plants which are installed in each one of the companies. This study indicates the differences of the financial results for supplying electricity and steam in both models proposed, describing the main variations and the reasons for those, besides identifying the main current tariff benefits in the legislation for the different classes of power plants and Energy Market. The summarized greenhouse gases inventory is presented for both industries as well, and a later assessment of environmental impact from the studied cogeneration plants in the overall GHG emissions in the two proposed scenarios is done. Finally, it is presented the relation analysis between electricity and steam supplying costs if compared with the greenhouse gases emissions levels for both proposed scenarios, and how public policies can act in order to guide emissions decreasing, since São Paulo State has promulgated a law in which establishes a major GHG emissions reduction to 2020.

**Keywords:** greenhouse gases emission, cogeneration, energy market.

## NOMENCLATURE

| | |
|---|---|
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| $CO_2eq$ | Equivalent carbon dioxide |
| Ee | Electrical-mechanical energy, kWh/h |
| Ef | Source energy, kWh/h |
| Et | Thermo energy, kWh/h |
| Fc% | Cogeneration factor, % |
| GHG | Greenhouse gases |
| $N_2O$ | Nitrous oxide |
| NCV | Net calorific value, GJ/unit |
| NPCC | National Plan on Climate change |
| SIN | Interconnected National System |
| SPCC | State Policy on Climate Change |
| TUSD | Distribution charge for use of the system |
| TUST | Transmission charge for use of the system |
| X | Weighting factor |

## Subscripts

| | |
|---|---|
| eq | equivalent |
| IPP | Independent Power Producer |

## INTRODUCTION

The greenhouse effect is a natural phenomenon that occurs in the terrestrial atmosphere, it is responsible for seizing part of the solar energy that enters into the planet as a short wave radiation and reflected back to outer space through the surface of the earth.

In a long term, the Earth has to irradiate energy to outer space at the same proportion it is absorbed from the sun (<http://mct.gov.br/index.php/content/view/49252.html>, 28 Nov. 2010). Such a natural seizure process of part of the solar energy is primordial to keep thermal balance and the basic conditions to the existence of life in our planet.

The gases which are in the atmosphere that present the physical property of absorbing and resending the reflected energy through the Earth's surface are called greenhouse gases (GHG), being either natural or entropic sources. The main greenhouse gases are the steam of water, carbon dioxide, methane and the nitrous oxide, besides the sulphur hexafluoride, hydrofluorocarbons and the perfluorocarbons.

Since the Industrial Revolution, it is being observed a higher elevation in the concentration of the greenhouse gases in the atmosphere, resulting in a great potential of the solar energy detention within the planet. Currently, the most severe case refers to the carbon dioxide ($CO_2$), which was noticed an elevation of 35% on its concentration in the atmosphere, turning from 280 ppm at the beginning of the Industrial Revolution to 379 ppm in 2005 (IPCC, 2007a). The emission of $CO_2$, in yearly terms, was amounted from 21 Gt/year to 38 Gt/year between 1970 an 2004, corresponding to a rising of about 80%. The $CO_2$ emissions represented 77% of the overall emissions of GHG in 2004 (IPCC, 2007a), demonstrating to be the main global warming "villain".

In November 9$^{th}$, 2009 the State of São Paulo promulgated the State Policy on Climate Change (SPCC) (São Paulo, 2009), which has established the commitment of the State towards the global climate changes, notoriously the global warming. This act establishes, among others, a target of 20% in the reduction of greenhouse gases emissions in São Paulo State until 2020, having as a reference the emissions along 2005. Every economy sectors, including the industrial one, must have their reduction targets established. The SPCC presents the actions and public policies that will have to be developed by São Paulo government in order to stimulate the usage of products or services environmentally cleaner, in spite of stimulating the most pollutant ones. Other governmental actions, such as subsides, unburdens, financings and taxations must be developed by the State.

The industrial sector will have to adequate itself in order to reach the objectives and targets established by the SPCC, in case of not reaching such further costs is going to be charged to the industries, once the State Policy determines that the doer of the environmental impact will have to be financially responsible towards the expenses on the damage caused in the environment (being a concept of polluter-pays).

Several brazilian industries use natural gas cogeneration plants inside its facilities in order to supply partially, or totally, the electricity and steam needs. However, it is necessary to do a careful environmental impact assessment of these power plants, mainly regarding greenhouse gases emission, since the companies will have to reach reduction targets defined by the government.

It is proposed a comparison between two different energy supply models for two manufacturing plants, the first one based on electricity supply from local grid and steam from natural gas fired steam generators, and a second model that considers the industries energy needs being partially supplied through natural gas cogeneration plants which are installed in each one of the companies.

This study presents the financial result and the greenhouse gases emissions impact in each one of the models.

## GREENHOUSE GASES INVENTORY

The State Policy on Climate Change, promulgated by Act No. 13,798/2009, clearly defined the São Paulo State objective in the reduction of greenhouse gases emissions until 2020. Before starting the natural gas cogeneration plants impact assessment in the GHG emissions for both factories, it is presented the 2010 summarized greenhouse gases inventory, not considering the use of cogeneration plants to supply factories energy needs.

The emissions levels presented in this paper were calculated following the Intergovernmental Panel on Climate Change (IPCC) guidelines, in accordance with IPCC (2006).

The focus of this work is not on the inventory preparation itself, but in the environmental and financial analysis of cogeneration plants, so it will not be presented details on inventory preparation, only the results will be showed.

Tables 1, 2 and 3 present the summarized greenhouse gases emissions inventory of factory 1, considering only key categories in 2010 (model with no cogeneration plant in operation). Intergovernmental Panel on Climate Change defines key category as "one that is prioritized within the inventory because its estimate has a significant influence on a total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals" (IPCC, 2006).

Table 1. GHG yearly emissions of factory 1 due to grid purchased electricity (no cogeneration plant in operation).

| | Month 1 | Month 2 | Month 3 | Month 4 | Month 5 |
|---|---|---|---|---|---|
| Grid purchased electricity | 7,612 | 6,947 | 7,216 | 7,113 | 7,075 |
| Emission factor (t $CO_2$/MWh) | 0.0211 | 0.0280 | 0.0243 | 0.0238 | 0.0341 |
| GHG emissions (t $CO_2$eq) | 161 | 195 | 175 | 169 | 241 |
| | Month 6 | Month 7 | Month 8 | Month 9 | Month 10 |
| Grid purchased electricity | 5,887 | 6,682 | 6,962 | 6,875 | 7,723 |
| Emission factor (t $CO_2$/MWh) | 0.0506 | 0.0435 | 0.0774 | 0.0907 | 0.0817 |
| GHG emissions (t $CO_2$eq) | 298 | 291 | 539 | 624 | 631 |
| | Month 11 | Month 12 | TOTAL | | |
| Grid purchased electricity | 7,503 | 8,317 | 85,912 | | |
| Emission factor (t $CO_2$/MWh) | 0.0869 | 0.0511 | 0.0512 | | |
| GHG emissions (t $CO_2$eq) | 652 | 425 | 4,400 | | |

[a]Source:<http://www.mct.gov.br/index.php/content/view/321144.html#ancora>, 25 Jan. 2011

Table 2. GHG yearly emissions of factory 1 due to natural gas consumption (no cogeneration plant in operation).

| | Consumption (m3) | Conversion factor [a] (GJ/m3) | Consumption (GJ) | $CO_2$ Emission factor [b] (kg $CO_2$/TJ) | $CO_2$ Emissions (t $CO_2$) |
|---|---|---|---|---|---|
| Natural gas | | | | | |
| Steam generators | 21,600,000 | 0.0367 | 792,390 | 56,100 | 44,453 |
| Cogeneration plant | 0 | 0.0367 | 0 | 56,100 | 0 |
| | | | | Total | 44,453 |
| | Consumption (m3) | Conversion factor [a] (GJ/m3) | Consumption (GJ) | $CH_4$ Emission factor [b] (kg $CH_4$/TJ) | $CH_4$ Emissions (t $CH_4$) |
| Natural gas | | | | | |
| Steam generators | 21,600,000 | 0.0367 | 792,390 | 1 | 0.792 |
| Cogeneration plant | 0 | 0.0367 | 0 | 1 | 0 |
| | | | | Total | 0.792 |
| | Consumption (m3) | Conversion factor [a] (GJ/m3) | Consumption (GJ) | $N_2O$ Emission factor [b] (kg $N_2O$ /TJ) | $N_2O$ Emissions (t $N_2O$) |
| Natural gas | | | | | |
| Steam generators | 21,600,000 | 0.0367 | 792,390 | 1 | 0.792 |
| Cogeneration plant | 0 | 0.0367 | 0 | 3 | 0 |
| | | | | Total | 0.792 |

[a] Source: Comgas (2008)
[b] Source: IPCC (2006)

Table 3. Total greenhouse gases yearly emissions of factory 1 (no cogeneration plant in operation).

| | Emissions (t) | GWP [a] | Emissions (t $CO_2$eq) |
|---|---|---|---|
| Natural gas | | | |
| $CO_2$ | 44,453 | 1 | 44,453 |
| $CH_4$ | 0.792 | 25 | 20 |
| $N_2O$ | 0.792 | 298 | 236 |
| Grid purchased electricity | | | |
| $CO_2$eq | 4,400 | 1 | 4,400 |
| Total emissions Factory 1 | | | 49,109 |

[a] Source: IPCC (2007b)

Tables 4, 5 and 6 present the summarized greenhouse gases emissions inventory of factory 2, considering only key categories in 2010 (model with no cogeneration plant in operation).

Table 4. GHG yearly emissions of factory 2 due to grid purchased electricity (no cogeneration plant in operation).

| | Month 1 | Month 2 | Month 3 | Month 4 | Month 5 |
|---|---|---|---|---|---|
| Grid purchased electricity | 7,148 | 6,456 | 6,763 | 6,390 | 6,298 |
| Emission factor (t $CO_2$/MWh) | 0.0211 | 0.0280 | 0.0243 | 0.0238 | 0.0341 |
| GHG emissions (t $CO_2$eq) | 151 | 181 | 164 | 152 | 215 |
| | Month 6 | Month 7 | Month 8 | Month 9 | Month 10 |
| Grid purchased electricity | 5,714 | 5,634 | 6,208 | 6,300 | 6,918 |
| Emission factor (t $CO_2$/MWh) | 0.0506 | 0.0435 | 0.0774 | 0.0907 | 0.0817 |
| GHG emissions (t $CO_2$eq) | 289 | 245 | 480 | 571 | 565 |
| | Month 11 | Month 12 | TOTAL | | |
| Grid purchased electricity | 7,126 | 7,709 | 78,663 | | |
| Emission factor (t $CO_2$/MWh) | 0.0869 | 0.0511 | 0.0512 | | |
| GHG emissions (t $CO_2$eq) | 619 | 394 | 4,027 | | |

[a]Source:<http://www.mct.gov.br/index.php/content/view/321144.html>, 25 Jan. 2011

Table 5. GHG yearly emissions of factory 2 due to natural gas consumption (no cogeneration plant in operation).

| | Consumption (m3) | Conversion factor [a] (GJ/m3) | Consumption (GJ) | $CO_2$ Emission factor [b] (kg $CO_2$/TJ) | $CO_2$ Emissions (t $CO_2$) |
|---|---|---|---|---|---|
| Natural gas | | | | | |
| Steam generators | 19,200,000 | 0.0368 | 706,568 | 56,100 | 39,638 |
| Cogeneration plant | 0 | 0.0368 | 0 | 56,100 | 0 |
| | | | | Total | 39,638 |
| | Consumption (m3) | Conversion factor [a] (GJ/m3) | Consumption (GJ) | $CH_4$ Emission factor [b] (kg $CH_4$/TJ) | $CH_4$ Emissions (t $CH_4$) |
| Natural gas | | | | | |
| Steam generators | 19,200,000 | 0.0368 | 706,568 | 1 | 0.707 |
| Cogeneration plant | 0 | 0.0368 | 0 | 1 | 0 |
| | | | | Total | 0.707 |
| | Consumption (m3) | Conversion factor [a] (GJ/m3) | Consumption (GJ) | $N_2O$ Emission factor [b] (kg $N_2O$ /TJ) | $N_2O$ Emissions (t $N_2O$) |
| Natural gas | | | | | |
| Steam generators | 19,200,000 | 0.0368 | 706,568 | 1 | 0.707 |
| Cogeneration plant | 0 | 0.0368 | 0 | 3 | 0 |
| | | | | Total | 0.707 |

[a] Source: Comgas (2008)
[b] Source: IPCC (2006)

Table 6. Total greenhouse gases yearly emissions of factory 2 (no cogeneration plant in operation).

| | Emissions (t) | GWP [a] | Emissions (t $CO_2$eq) |
|---|---|---|---|
| Natural gas | | | |
| $CO_2$ | 39,638 | 1 | 39,638 |
| $CH_4$ | 0.707 | 25 | 18 |
| $N_2O$ | 0.707 | 298 | 211 |
| Grid purchased electricity | | | |
| $CO_2$eq | 4,027 | 1 | 4,027 |
| Total emissions Factory 2 | | | 43,894 |

[a] Source: IPCC (2007b)

## COGENERATION POWER PLANTS CHARACTERISTICS AND INDUSTRIES ENERGY NEEDS

Table 7 shows the cogeneration power plants characteristics, besides the energy consumption needs of the industrial facilities studied.

Table 7. Cogeneration power plants characteristics and energy consumption needs of the industrial facilities (monthly average).

| | Factory 1 | Factory 2 |
|---|---|---|
| Factories monthly consumption | | |
| Electricity (MWh) | 7,159 | 6,555 |
| Process steam (t) | 22,500 | 20,000 |
| Cogeneration plant | | |
| Utilization factor (%) | 90% | 90% |
| Installed capacity (MW) | 8.4 | 6.0 |
| Monthly electricity generation (MWh) | 5,519 | 3,942 |
| Specific natural gas consumption ($m^3$/h) | 3,400 | 2,300 |
| Natural gas monthly consumption ($m^3$) | 2,233,800 | 1,511,100 |
| Monthly steam generation (t) | 17,506 | 10,555 |

As from data listed in Tab. 7, the environmental and financial impacts will be evaluated for both energy supply models proposed.

### Model 1

This model considers all electricity supply from local grid and steam from natural gas fired steam generators in each one of the factories.

### Model 2

This model considers the industries energy needs being partially supplied through natural gas cogeneration plants which are installed in each one of the companies. The remaining energy needs are supplied with electricity from local grid and steam from natural gas fired steam generators.

Table 8 presents energy supply sources to factories 1 and 2 for each proposed model.

Table 8. Energy supply sources for each proposed model.

| | Model 1 | Model 2 |
|---|---|---|
| Factory 1 | | |
| Grid purchased electricity (MWh) | 7,159 | 1,641 |
| Electricity from cogeneration plant (MWh) | 0 | 5,519 |
| Steam from steam generators - boilers (t) | 22,500 | 4,994 |
| Steam from cogeneration plant (MWh) | 0 | 17,506 |
| Factory 2 | | |
| Grid purchased electricity (MWh) | 6,555 | 2,613 |
| Electricity from cogeneration plant (MWh) | 0 | 3,942 |
| Steam from steam generators - boilers (t) | 20,000 | 2,494 |
| Steam from cogeneration plant (MWh) | 0 | 17,506 |

## FINANCIAL ASSESSMENT

Brazilian legislation establishes benefits to some classes of electricity generators sources, including cogeneration power plants. These benefits may be applied either in electricity tariffs or in natural gas tariffs, or in both ones.

### Benefits on electricity charges

The National Electricity Agency (ANEEL), in order to stimulate the electricity renewable sources use in the energy matrix, has established in the legislation some criteria for power plants (or electricity end consumers) take advantages in electricity tariffs.

### Discounts in the Charges for use of the system

The Resolution 77/2004 stipulates the requirements to take the discount in the Distribution charge for use of the system (TUSD) and in the Transmission charge for use of the system (TUST). This resolution establishes 50% discount on distribution and transmission charges, reflecting in the generation and consumption of the following electricity sources: Hydroelectric power plants with installed capacity less or equal 1MW, Small hydroelectric plants, Solar photovoltaic energy, Wind energy, Biomass and Qualified cogeneration.

Furthermore, it is defined 100% discount on TUSD and TUST charges for power plants burning at least 50% of biomass from municipal solid wastes, animal and vegetable waste digesters, landfill gas and sludge from wastewater treatment plants.

### Concept of Qualified cogeneration

The Resolution 235/2006 stipulates the qualification criteria for cogeneration ventures. This resolution defines Qualified cogeneration as “attribute granted to cogenerators which meet the minimum requirements for rational energy use, as described in legislagion, in order to participate in the cogeneration incentive policies”.

According to this resolution, cogeneration plants should comply with the following energy efficiency minimum requirements to take advantage in the incentives described in the previous topic:

$$\frac{Et}{Ef} \geq 15\% \qquad (1)$$

$$\left(\frac{Et}{Ef}\right) \div X + \frac{Ee}{Ef} \geq Fc\% \qquad (2)$$

where, according to ANEEL (2006),

• *Ef* is the Source energy, kWh/h. Input energy in the cogeneration plant, in its average operative system, based on the specific energy content, which in the case of fuels is the net calorific value (NCV);

• *Ee* is the Electrical-mechanical energy, kWh/h. Electrical-mechanical energy resulting from cogeneration power plant, in its average operative system, in net basis, discounting from generated gross energy the consumption due to plant auxiliary services;

• *Et* is the Thermo energy, kWh/h. Thermo energy provided by cogeneration power plant, in its average operative system, in net basis, discounting from gross energy provided to the process the low potential heat coming back to the plant;

• *Fc%* is the Cogeneration factor. Parameter defined due to the installed capacity and cogeneration plant source, bringing closer to Exergetic Efficiency concept; and

• *X* is the Weighting factor. Dimensionless parameter defined due to the installed capacity and cogeneration plant source, derived from the relation between thermo and electrical-mechanical reference efficiency, in conversion processes to obtain these energy types separately.

Table 9 shows values for Cogeneration factor (Fc%) and Weighting factor (X) (ANEEL, 2006).

As from Eq. (1) and Eq. (2), it was evaluated if the power plants installed at factories 1 and 2 can be classified as Qualified cogeneration. Both power plants meet requirements established in the legislation, as shown in Tab. 10.

Thus, cogeneration plants from factories 1 and 2 can take discounts in the charge for use of the system. There are two options relative to power plants classification at National Electricity Agency (ANEEL), depending on the manner in which power is retailed. In order to obtain the benefit in the tariff for use of the system, cogeneration plant must be classified as Independent Power Producer (IPP), which is defined as “a corporate legal entity or companies grouped together in consortia that are awarded concessions or authorizations to produce electricity and sell it, total or partially, at their own account and risk" (ANEEL, 1996). In this case study, in order to take the discount, the industries would sell the produced electricity to themselves.

Table 9. Cogeneration factor (Fc%) and Weighting factor (X) of cogeneration power plants.

| Source/installed capacity | X | Fc% |
|---|---|---|
| Petroleum-derived, Natural gas and Coal | | |
| Up to 5 MW | 2.14 | 41 |
| Between 5 MW and 20 MW | 2.13 | 44 |
| Over 20 MW | 2.00 | 50 |
| Other fuels | | |
| Up to 5 MW | 2.50 | 32 |
| Between 5 MW and 20 MW | 2.14 | 37 |
| Over 20 MW | 1.88 | 42 |
| Process heat recovery | | |
| Up to 5 MW | 2.60 | 25 |
| Between 5 MW and 20 MW | 2.17 | 30 |
| Over 20 MW | 1.86 | 35 |

Table 10. Qualification requirements assessment for cogeneration plants installed at factories 1 and 2.

| Requirements defined in the legislation | | | | | | Calculated value |
|---|---|---|---|---|---|---|
| Factory 1 | Et | Ef | Ee | X | Fc% | Factory 1 |
| $\frac{Et}{Ef} \geq 15\%$ | 21,722 | 34,647 | - | - | - | 63% |
| $\left(\frac{Et}{Ef}\right) \div X + \frac{Ee}{Ef} \geq Fc\%$ | 21,722 | 34,647 | 7,560 | 2.13 | 44% | 51% |
| Factory 2 | Et | Ef | Ee | X | Fc% | Factory 2 |
| $\frac{Et}{Ef} \geq 15\%$ | 13,097 | 23,437 | - | - | - | 56% |
| $\left(\frac{Et}{Ef}\right) \div X + \frac{Ee}{Ef} \geq Fc\%$ | 13,097 | 23,437 | 5,400 | 2.13 | 44% | 49% |

Other option would be classify the cogeneration plants as Self-producer, which is defined as "an individual or corporate legal entity, or companies grouped into a consortium, that are awarded a concession or authorization to produce electricity for their own use" (ANEEL, 1996). In this situation, there is not any electricity trade.

## Benefits on natural gas charges

The natural gas incentives to cogeneration plants vary widely, depending on the geographical location of the plant, since depends on the natural gas grid.

The Decree CSPE-1/1999 defines the different tariff levels and the natural gas consumption unit classification for consumption units located at concession area of the grid responsible to supply natural gas to the factories. This decree presents the "Cogeneration class", so that all natural gas billed for cogenerators has differentiated tariffs if compared to consumption units receiving the regular "Industrial class" natural gas.

Tariffs benefits offered to the cogeneration plants depends on natural gas contracted volume with the grid. In this case study, the discount is around 26%. In other words, the natural gas burned in the cogeneration plants studied is subsidized.

Table 11 shows the financial assessment result of factory 1 for the proposed models, considering the electricity and natural gas charges benefits. Model 2 was divided into Model $2_{IPP}$ (power plant classified as Independent Power Producer) and Model $2_{SP}$ (power plant classified as Self-producer).

Table 11. Financial assessment result of factory 1 cogeneration plant (monthly values).

| | Model 1 | Model $2_{IPP}$ | Model $2_{SP}$ |
|---|---|---|---|
| Local grid cost | | | |
| Contracted demand [R$] | 256,336 | 256,336 | 134,257 |
| Electricity consumption [R$] | 227,881 | 52,217 | 227,881 |
| Energy trader cost [R$] | 1,031,083 | 243,354 | 267,198 |
| Natural gas cost | | | |
| Industrial tariff natural gas [R$] | 1,404,000 | 311,636 | 311,636 |
| Cogeneration tariff natural gas [R$] | 0 | 1,295,604 | 1,295,604 |
| Operation and maintenance average cost [R$] | 0 | 360,000 | 360,000 |
| Total monthly cost [R$] | 2,919,300 | 2,519,147 | 2,596,576 |

Model 2, with the plant classified as Independent Power Producer, is the best option for factory 1. The yearly saving is R$ 2,969,628 if compared to Model 1.

Table 12 presents the financial assessment result of factory 2 for the proposed models.

Table 12. Financial assessment result of factory 2 cogeneration plant (monthly values).

| | Model 1 | Model $2_{IPP}$ | Model $2_{SP}$ |
|---|---|---|---|
| Local grid cost | | | |
| Contracted demand [R$] | 269,880 | 269,880 | 135,420 |
| Electricity consumption [R$] | 206,359 | 82,265 | 206,359 |
| Energy trader cost [R$] | 944,086 | 387,650 | 404,682 |
| Natural gas cost | | | |
| Industrial tariff natural gas [R$] | 1,248,000 | 589,342 | 589,342 |
| Cogeneration tariff natural gas [R$] | 0 | 876,438 | 876,438 |
| Operation and maintenance average cost [R$] | 0 | 160,000 | 160,000 |
| Total monthly cost [R$] | 2,668,325 | 2,365,575 | 2,372,240 |

Model 2, with the plant classified as Independent Power Producer, is the best option for factory 2. The yearly saving is R$ 2,596,728 if compared to Model 1.

## ENVIRONMENTAL ASSESSMENT

Natural gas is the fuel burned at studied power plants. This type of technology interferes in the industries greenhouse gases emissions levels, so it is recommended to perform an impact assessment of GHG emissions reduction due to cogeneration plants.

According to ANEEL (<http://www.aneel.gov.br/aplicacoes/capacidadebrasil/OperacaoCapacidadeBrasil.asp>, 11 Jan. 2011), renewable sources represents 74.3% of installed capacity from brazilian electricity matrix, so that greenhouse gases emissions due to electricity generation are significantly small. Table 13 presents the average greenhouse gases emissions to different energy generation sources, as adapted from Sovacool (2008).

Table 13. Greenhouse gases emissions for different sources of electricity.

| Technology | Emissions (kg $CO_2$eq / MWh) |
|---|---|
| Wind | 9 |
| Hydroelectric | 10 |
| Biogas | 11 |
| Solar thermal | 13 |
| Biomass | 28 |
| Solar PV | 32 |
| Geothermal | 38 |
| Nuclear | 66 |
| Natural gas | 443 |
| Fuel cell | 664 |
| Diesel | 778 |
| Heavy oil | 778 |
| Coal | 1,005 |

Clearly, the use of electricity from fossil sources (like in the cogeneration plants studied) it is not advantageous on greenhouse gases emissions viewpoint if compared to renewable sources. Table 14 presents the equivalent greenhouse gases emissions result of factory 1 for the Models 1 and 2.

Table 15 presents the equivalent greenhouse gases emissions result of factory 2 for the Models 1 and 2.

Table 14. Greenhouse gases yearly emissions of factory 1 in the Models 1 and 2.

| Emissions (t $CO_2$eq) | Model 1 | Model 2 |
|---|---|---|
| Natural gas | | |
| $CO_2$ | 44,453 | 65,033 |
| $CH_4$ | 20 | 29 |
| $N_2O$ | 236 | 932 |
| Grid purchased electricity | | |
| $CO_2$eq | 4,400 | 1,016 |
| Total emissions factory 1 | 49,109 | 67,010 |

Table 15. Greenhouse gases yearly emissions of factory 2 in the Models 1 and 2.

| Emissions (t $CO_2$eq) | Model 1 | Model 2 |
|---|---|---|
| Natural gas | | |
| $CO_2$ | 39,638 | 55,978 |
| $CH_4$ | 18 | 25 |
| $N_2O$ | 211 | 694 |
| Grid purchased electricity | | |
| $CO_2$eq | 4,027 | 1,610 |
| Total emissions factory 2 | 43,894 | 58,307 |

It´s easy to observe a major increase in the GHG emissions levels when the cogeneration power plants are operating (Model 2).

Greenhouse gases emissions quantifying due to grid electricity consumption in both models was done using the average emission factors proposed by brazilian Science and Technology Ministry (MCT) for inventory preparation (<http://www.mct.gov.br/index.php/content/view/321144.html#ancora>, 25 Jan. 2011).

According to Tables 1 and 4 previously presented, the average emission factors of factories 1 and 2 are:

1) 0.0281 t $CO_2$eq/MWh for factory 1 (yearly average)
2) 0.0277 t $CO_2$eq/MWh for factory 2 (yearly average)

The values showed above are substantially low. Nonetheless, according to Esparta studies (2008), the fact that Brazil presents an electrical energy generation matrix relatively clean, it does not mean necessarily that the “avoided emissions in the operation margin” of the brazilian Interconnected National System (SIN) are going to be small. In such a case, if the cogeneration plants do not operate, the GHG emissions at SIN to compensate the increase in energy consumption along the brazilian electrical system (due to factories 1 and 2) could come from power plants with higher emission factors, as in the case of thermal coal, residual fuel oil, diesel oil and natural gas power plants.

Therefore, it is necessary to evaluate the real impact of greenhouse gases emissions due to cogeneration plants very carefully, since electricity generated inside the industries reduces the electricity supply through power plants running on operation margin of SIN, which usually are plants that burns fossil fuels, and presents emission factors higher than the proposed by MCT for inventory preparation (<http://www.mct.gov.br/ index.php/content/view/321144.html#ancora>, 25 Jan. 2011).

## RESULTS AND DISCUSSION

Table 16 shows the financial and environmental analysis result for factories 1 and 2 in both proposed models.

Table 16. Environmental and financial assessment result (yearly values).

| | Model 1 | Model 2 | Diference (%) |
|---|---|---|---|
| Factory 1 | | | |
| Electricity and steam cost (R$) | 35,031,599 | 30,229,763 | -14% |
| Greenhouse gases emissions (t $CO_2$eq) | 49,109 | 67,010 | 36% |
| Factory 2 | | | |
| Electricity and steam cost (R$) | 32,019,897 | 28,386,894 | -11% |
| Greenhouse gases emissions (t $CO_2$eq) | 43,894 | 58,307 | 33% |

As mentioned, figures presented in Tab. 16 uses emission factors of grid electricity consumption proposed by brazilian Science and Technology Ministry for inventory preparation (<http://www. mct.gov.br/ index.php/content/view/321144.html# ancora>, 25 Jan. 2011), resulting in increases of 41% and 37% in the greenhouse gases emissions levels at factories 1 and 2 respectively.

Nevertheless, the use of cogeneration plants to supply electrical energy demands of both industries replaces the use of power plants that operate in the operation margin of SIN, which are able to present average emission factors higher than those suggested by the MCT in the elaboration of corporate inventories, causing thus distortions in the analysis of the real environmental impact of the power plants. In this case, the emission factor of the cogeneration plants must be compared with the average emission factor of the plants that operate on SIN operation margin, that is, the emission factor proposed by MCT to elaborate inventories would not be used, but the emission factor of operation margin should be used.

Science and Technology Ministry has defined the average emission factors for power plants running on operation margin (<http://www.mct.gov.br/index. php/content/view/321144.html#ancora>, 26 jan 2011). Table 17 shows the values proposed between 2006 and 2010.

Table 17. Emission factors for power plants running on operation margin.

| Year | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|
| Margin Emission Factor | 0.2023 | 0.1842 | 0.3112 | 0.1635 | 0.2835 |

National Plan on Climate change (NPCC, 2008) adopts 0.29 t $CO_2$eq/MWh as emission factor in order to estimate the greenhouse gases emissions reduction potential resulting from future initiatives which may lead to grid electricity use decreasing.

Studies from Reis (2009) point to an increase trend of emission factor from electricity consumed in operation margin. According to Reis calculation, margin emission factor will be 0.37 t $CO_2$eq/MWh by 2017.

Table 18 presents the values of the average emission factors of the power plants that operate on SIN operation margin that would make the Models 1 and 2 to have the same final value of greenhouse gases equivalent emissions, that is, it is shown as from the emission factor value (break even) of the plants working within the operation margin that the cogeneration plants would be favorable if compared to the Model 1 (which does not consider the use of the plants).

Table 18. Average emission factor break even of power plants running on SIN operation margin in order to match greenhouse gases equivalent emissions in Models 1 and 2 for both factories.

| Break even | Average emission factor from SIN plants (t $CO_2$eq/MWh) | Emissions (t $CO_2$eq) |
|---|---|---|
| Factory 1 | 0.3215 | 67,010 |
| Factory 2 | 0.3559 | 58,307 |

## CONCLUSIONS

It is concluded that the cogeneration power plants studied in this work propitiate a huge financial advantage to the companies, mainly due to benefits in legislation applied to electricity and natural gas charges.

From the greenhouse gases equivalent emissions point of view, the cogeneration plants studied have shown to be very harmful when the emission factors suggested by MCT are used in the preparation of the inventories (<http://www.mct.gov.br/ index.php/ content/view/321144.html#ancora>, 25 Jan. 2011), which is the official source for inventories elaboration. The use of those emission factors leads to a substantial addition in the emission levels, once it uses the average emission factor of brazilian electrical system. Yet, it is necessary to evaluate and compare the impact of those cogeneration plants using the emission factors of the power plants running on operation margin, which generally burn fossil fuels and present higher emission factors.

Still in relation to the greenhouse gases emissions, the studied cogeneration plants are able to proportionate an effective reduction in the GHG emissions in the case the emission factors of the power plants running on operation margin of brazilian electrical system are superior to 0.3221 and 0.3590 t $CO_2$eq/MWh, for the factories 1 and 2 respectively.

## REFERENCES

ANEEL, 1996, Decreto n.º 2003 de 1996, Agência Nacional de Energia Elétrica. *(in*

*Portuguese)*

ANEEL, 2004, Resolução Normativa n.º 77 de 2004, Agência Nacional de Energia Elétrica. *(in Portuguese)*

ANEEL, 2006, Resolução Normativa n.º 235 de 2006, Agência Nacional de Energia Elétrica. *(in Portuguese)*

Brasil, 2008, Plano Nacional sobre Mudança do Clima, Governo Federal, 2008. *(in Portuguese)*

Comgás, 2008, FISPQ do gás natural fornecido pela Comgás (Ficha de informações de segurança de produtos químicos). *(in Portuguese)*

CSPE, 1999, Portaria CSPE-1 de 1999, Comissão de Serviços Públicos de Energia. *(in Portuguese)*

Esparta, A. R. J., 2008, Redução de Emissões de Gases de Efeito Estufa no Setor Elétrico Brasileiro: a Experiência do Mecanismo de Desenvolvimento Limpo do Protocolo de Quioto e uma Visão Futura, Doctoral Thesis, Programa Interunidades de Pós-graduação em Energia, Universidade de São Paulo, São Paulo. *(in Portuguese)*

IPCC, 2006, IPCC Guidelines for National Greenhouse Gas Inventories, Intergovernmental Panel on Climate Change.

IPCC, 2007a, 2007, Climate Change 2007: Synthesis Report, Intergovernmental Panel on Climate Change.

IPCC, 2007b, 2007, IPCC Fourth Assessment Report: Climate Change 2007, Intergovernmental Panel on Climate Change.

Reis, T. V. M., 2009, Metodologia para Estimar a Linha de Base de Projeto MDL Conectado a Sistema Elétrico: uma Abordagem Prospectiva, Doctoral Thesis, Escola Politécnica, Universidade de São Paulo, São Paulo. *(in Portuguese)*

São Paulo, 2009, Act 13.798: State Policy on Climate Change, São Paulo State Government.

Sovacool, B. K., 2008, Valuing the Greenhouse Gas Emissions from Nuclear Power: a Critical Survey, Energy Policy, Vol. 36, pp. 2940-2953.

Grant, L. D. R, Adams, R. D., Da Silva, F. M., 2009, Effect of the Temperature on the Strength of Adhesively Bonded Single Lap and T Joints for the Automotive Industry, International Journal of Adhesion and Adhesives, Vol. 29, pp. 535-542.

Heslehurst, R. B., 1999, Observations in the Structural Response of Adhesive Bondline Defects, International Journal of Adhesion and Adhesives, Vol. 19, pp. 133-154.

Kahraman, R., Sunar, M., and Yilbas, B., 2008, Influence of Adhesive Thickness and Filler Content on the Mechanical Performance of Aluminum Single-Lap Joints Bonded with Aluminum Powder Filled Epoxy Adhesive, Journal of Materials Processing Technology, Vol. 205, pp. 183-189.

Knox, E. M., and Cowling, M. J., 2000, Durability Aspects of Adhesively Bonded Thick Adherend Lap Shear Joints, International Journal of Adhesion and Adhesives, Vol. 20, pp. 323-331.

Loh, W. K., Crocombe, A. D., Abdel, M. M., Ahab, W., and Ashcroft, I. A., 2002, Environmental Degradation of the Interfacial Fracture Energy in an Adhesively Bonded Joint, Engineering Fracture Mechanics, Vol. 69, pp. 2113-2128.

Mathews, F. L., and Hollaway, L. C., 1999, *Handbook of Polymer Composites for Engineers* Woodhead Publishing Limited.

Neves, P. J. C., Silva, L. F. M, and Adams, R. D, 2009, Analytical Models of Adhesively Bonded Joints-Part II: Comparative Study, International Journal of Adhesion and Adhesives, Vol. 29, pp. 331-341.

Silva, A. H. M. F. T., 2010, Critério de Falha para Juntas Coladas Submetidas a Carregamentos Complexos, Doctoral Thesis, Universidade Federal Fluminense, Niteroi, RJ. (*in Portuguese*)

Silva, L. F. M. , Carbas, R. J. C., Critchlow, G. W., Figueiredo, M. A. V, and Brown, K., 2009, Effect of Material, Geometry, Surface Treatment and Environment on the Shear Strength of Single Lap Joints, International Journal of Adhesion and Adhesives, Vol. 29, pp. 621-632.

Zhang, Y., Vassilopoulos, P. A., and Keller, T.,2010, Effects of Low and High Temperatures on Tensile Behavior of Adhesively-Bonded GFRP Joints, Composite Structures, Vol. 92, No. 7, pp. 1631-1639.