ESTIMATE OF ECOLOGICAL EFFICIENCY FOR THERMAL POWER PLANTS IN BRAZIL

Electo Eduardo Silva Lora
Federal University of Itajubá / Thermal Systems Study Group – NEST
Av BPS 1303, CP 50, Itajubá, MG, CEP 37.500-903 - Brazil
electo@iem.efei.br

Karina Ribeiro Salomon
Federal University of Itajubá / Thermal Systems Study Group – NEST
Av BPS 1303, CP 50, Itajubá, MG, CEP 37.500-903 - Brazil
karina@iem.efei.br

Abstract: Global warming and the following climatic changes that will come as a consequence of the increase of CO₂ concentration in the atmosphere have increased the world’s concern regarding the reduction of these emissions, mainly in developed countries, which pollute the most. Thermoelectric generation, as well as other industrial activities such as chemical and petrochemical ones, are related to the emission of pollutants that are harmful to humans, animals and plants. The emissions of carbon oxides (CO and CO₂) and nitrous oxide (N₂O) are directly related to the greenhouse effect. The negative effects of sulfur oxides (SO₂ and SO₃ named SOₓ) and the nitrogen oxides (NOₓ) are their contribution to the formation of acid rain and their impacts on human health and on the biota in general. This study intends to evaluate the environmental impacts of the atmospheric pollution resulting from the burn of fossil fuels. This study considers the emissions of CO₂, SOₓ, NOₓ and PM in an integral way and they are compared to the international air quality standards that are in force, using a parameter called ecological efficiency (ε).

Keywords: thermal generation, atmospheric emission, ecological efficiency.

1. Introduction

Thermal generation, as well as other industrial activities such as chemical and petrochemical, presents polluting emissions that are harmful to the health of humans, animals and plants. The emissions of carbon oxides (CO and CO₂) and nitrous oxide (N₂O) are directly related to the greenhouse effect. The negative effects of sulfur oxides (SO₂ and SO₃, called SOₓ) and the nitrogen oxides (NOₓ) are their contribution towards acid rain.

The global warming, caused by the increase of the amount of CO₂ in the atmosphere, has increased the world’s concern for reducing these emissions, mainly in developed countries, which are the greatest polluters. This way, in December 1997, 38 countries signed the Kyoto Protocol. It established that the industrialized countries would have to reduce their emission of greenhouse gases by 5%, at least, by the period between 2008 and 2012 in relation to the levels registered in 1990. This commitment promised to produce a shift in the historical trend of growing emissions started in those countries. After a few years, some countries have ratified the agreement, others are about to, but the USA decided not to ratify the Protocol, although it is the country presenting the highest emission of CO₂. After the Kyoto Protocol, there have been other agreements such as the Bonn Convention that was held in July 2001 and was a political mark on the slow international negotiations about the Kyoto Protocol. The Agreement created the fundamental bases for the countries to be able to ratify and implement the Protocol and for the negotiation of emissions that will be even more reduced in the future. The financing package included a commitment made by The USA, New Zealand and Switzerland to give US$140 million to the developing countries every year until 2005, and in 2008, a new analysis will be carried out. Another important agreement was closed at the Marrakesh Conference in October 2001. Its goal was to solve Bonn’s pending issues and conclude the conversion of the Agreement into a United Nations formal and Legal text.

Control methods are used at thermal power plants for reducing the emissions of polluting gases. A special attention is paid for CO₂, for the increase in its concentration makes the Earth temperature rise. Although it is not toxic, its emission, reaching high concentrations, during the combustion process is inevitable and there are no control methods that can be used for reducing its emission.

This study aims at evaluating the environmental impacts resulting from the burning of fossil fuels and its conversion into electricity in thermal power plants. Emissions of CO₂, SOₓ, and NOₓ were considered in an integral way and the international air quality standards were used as a reference. The ecological efficiency parameter (ε) was used. This parameter was proposed by two Rumanian scientists, Cardu and Baica (1999). Our study broadens its scope and its application area considering:
- The effect of the emissions of particulate matter that is not included in the original proposal;
- NOₓ emissions are considered by using emission factors for different conversion technology and fuel combinations. This makes it possible to take the effects of operating parameters such as flame temperature and the rate of air in the NOₓ emission into account.
Cardu and Baica (1999) used the ecological efficiency parameter just for steam cycles using coal. In our study, this parameter was extended to combined cycle plants using natural gas, internal combustion engines and conventional and advanced cycles using biomass as fuel.

This efficiency ($\varepsilon$) evaluates, in an integral way, the environmental impacts caused by emissions released by thermal power plants. The evaluation considered the combustion of 1 kg of fuel, not the quantity of gases released from a thermal plant per unit of useful energy generated (Cardu and Baica, 1999), as emission standards.

### 2. Methodology for the calculation of ecological efficiency

As a reference during the analysis, the highest permissible concentrations of toxic substances in the air are considered. The World Health Organization’s air quality standard (WHO apud Lora, 2000) was used for this analysis, and they are presented in Table 1. CO$_2$ does not have emission standards although it is the main cause of the greenhouse effect and climatic changes. Some countries have been implementing carbon taxes, which penalize those who release high concentrations of CO$_2$ and encourage reductions establishing a maximum limit for its emission. Based on these standards and considering the maximal permissible CO$_2$ concentration, which is 10000 mg/m$^3$ (Cardu e Baica, 1999), one can find the coefficients for the calculation of the concentration of a hypothetical “integral” pollutant called “Equivalent Carbon Dioxide” (CO$_2$)$_e$, Table (2). According to Cardu et al (1999) for the calculation of this coefficient one has to divide the value of the CO$_2$ maximal permissible concentration by the air quality standards corresponding to NO$_x$, SO$_x$, and PM in 1 hour average. The air quality national standard for particulate matter (PM) according to CONAMA’s (National Environmental Council) Resolution nº 3, 28 June.90, is 150 µg/m$^3$. The following technologies and fuels were evaluated: combined cycle (gas turbine/steam turbine) – natural gas, internal combustion engine - diesel, open cycle gas turbine – natural gas, steam cycle (boiler/steam turbine) – coal (bituminous) and steam cycle (TCE – 80 and BIG/GT) – sugar cane bagasse.

#### Table 1. World Health Organization air quality standards (WHO, 2000) (Lora, 2002).

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Standards</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO$_x$</td>
<td>1 hour average: 200 µg/m$^3$ &lt;br&gt;Annual average*: 40 µg/m$^3$</td>
<td>Minimal concentration that affects people who have asthma in 30-110 minutes of exposure: 565 µg/m$^3$. Respiratory effects on children having a long-time exposure: 50-75 µg/m$^3$. Natural concentration in clean air: 1 – 9 µg/m$^3$. Annual average value in cities: 20 – 90 µg/m$^3$.</td>
</tr>
<tr>
<td>SO$_x$</td>
<td>1 hour average: 125 µg/m$^3$ &lt;br&gt;Annual average*: 50 µg/m$^3$</td>
<td>Minimal concentration that affects people who have asthma in 10 minutes of exposure: 500 µg/m$^3$. Minimal concentration presenting adverse effects in a long-time exposure: 100 µg/m$^3$. Natural concentration in clean air: 1 – 9 µg/m$^3$. Annual average value in cities: 20 – 40 µg/m$^3$.</td>
</tr>
</tbody>
</table>

*- Annual average in urban areas.

#### Table 2: Multiplication factor of SO$_x$ gases, PM and NO$_x$ in comparison with CO$_2$.

<table>
<thead>
<tr>
<th>Maximal acceptable limit (µg/m$^3$)</th>
<th>Multiplication factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>SO$_x$</td>
</tr>
<tr>
<td>10000</td>
<td>125</td>
</tr>
</tbody>
</table>

a- CO$_2$/SO$_x$ (Cardu and Baica, 1999).  
b- CO$_2$/NO$_x$ (Cardu and Baica, 1999).  
c- CO$_2$/PM (Cardu and Baica, 1999).

Thus, the expression for (CO$_2$)$_e$ will be presented in Eq. (1):

$$\text{(CO}_2\text{)}_e = \text{(CO}_2\text{)} + 80 \times \text{(SO}_x\text{)} + 50 \times \text{(NO}_x\text{)} + 67 \times \text{(PM)} \quad (1)$$

The equation above shows that the sulfur oxide equivalent in (CO$_2$) is (SO$_x$)$_e = 80 \times \text{(SO}_x\text{)}$, that is, the equivalent concentration of SO$_x$ presenting the same environmental impact as a kg of CO$_2$. The same thing will happen in relation to the other pollutants: nitrogen oxide equivalent in (CO$_2$) will be (NO$_x$)$_e = 50 \times \text{(NO}_x\text{)}$ and the particulate matter equivalent in (CO$_2$) will be (PM)$_e = 67 \times \text{(PM)}$. The best fuel, ecologically speaking, is the one that presents the least
amount of equivalent carbon obtained as the result of its burning. In order to quantify the environmental impact caused by burning a fuel, a “pollution indicator” \((\Pi_g)\) was defined, Equation (2), and it can be calculated as follows:

\[
\Pi_g = \frac{(\text{CO}_2)_e}{\text{Qi}}
\]  

(2)

where \((\text{CO}_2)_e\) is expressed in kg/kg\(_{\text{fuel}}\) (kg of CO\(_2\) per kg of fuel), \(\text{Qi}\) is the LHV (low heat value of the fuel) expressed in MJ/kg and \(\Pi_g\) (pollution indicator) is expressed in kg/MJ, where kg refers to the mass of \((\text{CO}_2)_e\).

First one must calculate, based on the chemical composition of the fuel, the volumes of CO\(_2\), SO\(_x\), NO\(_x\), PM, \((\text{SO}_x)_e\), \((\text{NO}_x)_e\), \((\text{PM})_e\) released during the combustion of 1 kg of fuel. After that the volume of \((\text{CO}_2)_e\) is calculated in accordance with Equation (1), based on chemical composition of the fuel. Finally the volume of the generated gases can be calculated. All of the concentrations must be expressed in kg/kg of fuel or kg/kg\(_{\text{fuel}}\). The equations in Table 3 were used for these calculations (3):

### Table 3: Equations for the calculation of the volume of the gases. (Nogueira, 2002)

<table>
<thead>
<tr>
<th>For solid and liquid fuels (Nm(^3)/kg)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{a}^°) (Theoretic combustion air volume)</td>
<td>(0.0889*(C+0.375<em>S)+0.265</em>H'-0.0333*O')</td>
</tr>
<tr>
<td>(V_{g}^°) (Combustion gas theoretical volume)</td>
<td>(V_{\text{RO}<em>2}^°+ V</em>{\text{N}<em>2}^°+ V</em>{\text{H}_2O}^°)</td>
</tr>
<tr>
<td>(V_{\text{CO}_2}^°) (Triatomic gases volume in combustion gases)</td>
<td>(V_{\text{CO}<em>2}^°+ V</em>{\text{SO}_2}^° = 0.01866*(C' + 0.375*S'))</td>
</tr>
<tr>
<td>(V_{\text{SO}_2}^°) (Sulfur dioxide theoretic volume in combustion gases)</td>
<td>(1.866*C'/100)</td>
</tr>
<tr>
<td>(V_{\text{N}_2}^°) (Nitrogen theoretic volume in combustion gases)</td>
<td>(0.7*S'/100)</td>
</tr>
<tr>
<td>(V_{\text{H}_2O}^°) (Water steam theoretic volume in combustion gases)</td>
<td>(0.111<em>H'+0.0124</em>W_t+0.0161*V_{a}^°)</td>
</tr>
<tr>
<td>For gaseous fuels (Nm(^3)/m(^3))</td>
<td></td>
</tr>
<tr>
<td>(V_{a}^°) (Theoretic combustion air volume)</td>
<td>(0.0476*[0.5*(\text{CO}+\text{H}_2)+1.5*\text{H}_2\text{S}-\text{O}_2+\Sigma(m+n/4)*\text{C}_m\text{H}_n\text{O}_2])</td>
</tr>
<tr>
<td>(V_{g}^°) (Combustion gas theoretical volume)</td>
<td>(V_{\text{RO}<em>2}^°+ V</em>{\text{N}<em>2}^°+ V</em>{\text{H}_2O}^°)</td>
</tr>
<tr>
<td>(V_{\text{SO}_2}^°) (Triatomic gases volume in combustion gases)</td>
<td>(V_{\text{CO}<em>2}^°+ V</em>{\text{SO}_2}^° = 0.01*(\text{CO}+\text{CO}+\text{H}_2\text{S}+\Sigma m*\text{C}_m\text{H}_n))</td>
</tr>
<tr>
<td>(V_{\text{N}_2}^°) (Nitrogen theoretic volume in combustion gases)</td>
<td>(0.79<em>V_{a}^°+0.01</em>N_2)</td>
</tr>
<tr>
<td>(V_{\text{H}_2O}^°) (Water steam theoretic volume in combustion gases)</td>
<td>(0.01*(\text{H}_2+\text{H}_2\text{S}+\Sigma n/2*\text{C}_m\text{H}<em>n+0.124<em>W_g+3.27</em>V</em>{a}^°))</td>
</tr>
<tr>
<td>(V_{g}^°) (Combustion gas real volume)</td>
<td>(V_{a}^°+1.0161*(\alpha-1)*V_{a}^°)</td>
</tr>
</tbody>
</table>

- for \(W_g\) a value of 10 g/m\(^3\) can be assumed.
- value of \(\alpha\) (Cortez and Lora, 1997).

The emission of NO\(_x\) per kg of fuel depends on several factors, for example, the combustion temperature and the air excess. In order to calculate the value of NO\(_x\), it is necessary to consider the value of emission factors of different technologies (Blustein, 2001; Sydkraff, 2001), taking into account the type of fuel that is being used, contrariwise to the methodology adopted by the reference (Cardu and Baica, 1999), who considers that the amount of NO\(_x\) in the gas is the emission maximal limit acceptable (emission standard) multiplied by the volume of the gas.

The calculation of the amount of particulate matter in the gas is based on the amount of ashes in the fuels. When polluting control methods are used, the removal efficiencies are \(\sigma_c\), \(\sigma_s\), \(\sigma_n\) e \(\sigma_{\text{PM}}\) for CO\(_2\), SO\(_x\), NO\(_x\) and PM, respectively. The \((\text{CO}_2)_e\) will be determined by Equation (3):

\[
(\text{CO}_2)_e = (1-\sigma_c)*\text{CO}_2 + 80*(1-\sigma_c)*\text{SO}_x + 50*(1-\sigma_n)*\text{NO}_x + 67*(1-\sigma_{\text{PM}})*\text{PM}
\]  

(3)

A brief overview of technologies used for the prevention and control of nitrogen oxides, sulfur oxides and particulates will be given next. The removal efficiency values were based on EPA, 1995.

Methods of preventing NO\(_x\) emissions, which are called pre-combustion (preventive) methods, are based on:

- Combustion maximum temperature reduction;
- Reduction in the amount of oxygen in the primary zone of the flame by organizing the process in several stages.

The existing control methods are: dry low NO\(_x\) burners (DLNB), re-circulation of combustion products, multiple stage combustion, low NO\(_x\) emission burners of (LNB), water injection in the combustion chamber and combustion in fluidized bed, whose efficiency ranges from 35% to 90 %. Another pre-combustion method is the gas re-burning (a joined combustion of natural gas and coal) whose efficiency ranges between 75% and 80%. Several preventive methods are used together in order to achieve high efficiency in relation to NO\(_x\) control, for they present additive properties.

Combination is also a possibility; preventive and corrective methods can be coupled to the same equipment in order to achieve successive reductions in the concentration of NO\(_x\) in the combustion gases. One example is the use of methods,
such as low NO\textsubscript{X} emission burners and multiple stage combustion together with corrective methods, for example, selective catalytic reduction. Post combustion methods, which are called corrective methods, are based on the injection of ammonia in order to reduce the NO\textsubscript{X} until it becomes N\textsubscript{2}, with or without the presence of a catalyst. They are: Selective Non-Catalytic Reduction (SNCR), with an efficiency ranging between 30% and 70%, and Selective Catalytic Reduction (SCR) presenting efficiencies from 60% to 90%. The most widespread methods of controlling SO\textsubscript{2} emissions are: wet desulfurization, whose efficiency ranges between 80% and 96% depending on the process (with lime, sodium carbonate, magnesium hydroxide, double cycle alkaline); spray dryer - 70% to 90%; and dry injection 50% to 70% respectively. Today, the most commonly used method is desulfurization by using lime due to its high efficiency. Within the past few years, it has been observed a tendency towards a reduction in wet desulfurization process costs. In Brazil, coal plants do not use desulfurization (FDG) and the SO\textsubscript{X} emission control is carried out based on the limitation of the amount of sulfur in the fuel. The most commonly used equipment for particulate control is: gas scrubbers, cyclones, electrostatic precipitators (ESP) and baghouse filters. Their efficiencies range between 85 and 99%. Thermal plants usually use only ESP and baghouse filters, and the use of the latter is still wider. The danger of the particulate is due to the fact that constitutes the most efficient way for the pollutants transport to the lungs.

The second step is to find out the value of the “Pollution indicator”, $\Pi_g$. In order to compare the different fuels and be able to have reference points of $\Pi_g$, two virtual fuels are used. One of them is very clean (pure hydrogen) with $\Pi_g = 0$ and the other is extremely polluting (pure sulfur) with $\Pi_g = 134$ kg/MJ. It is evident that high efficient advanced technologies need a smaller amount of fuel to generate each kWh of electricity. This makes the specific polluting emission smaller. Thus, it is possible to see that the technological development together with a better conversion efficiency constitutes a determining factor towards the reduction of environmental impacts caused by thermoelectric generation. Table 4 presents the characteristics of the fuels (Cardu and Baica, 1999):

<table>
<thead>
<tr>
<th>Fuels</th>
<th>S%</th>
<th>(CO\textsubscript{2}) (kg/kg_fuel)</th>
<th>$Q_i$ (MJ/kg)</th>
<th>$\Pi_g$ (kg/MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur</td>
<td>100</td>
<td>1400</td>
<td>10.45</td>
<td>134</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>-</td>
<td>0</td>
<td>10.742</td>
<td>0</td>
</tr>
</tbody>
</table>

3. Ecological efficiency

Ecological efficiency is an indicator that allows the evaluation of the environmental impacts of the gaseous emissions released by a thermal power plant by using the comparison of the polluting emissions hypothetically integrated (CO\textsubscript{2} equivalent emissions that depend on the fuel composition, on the technology used and on the efficiency of pollution control systems) with the air quality standards. The conversion efficiency is also considered as a determining factor over the specific emissions, express in fractional number.

The ecological efficiency ($\varepsilon$) is calculated by using Equation (4) (Cardu and Baica, 1999):

$$
\varepsilon = \left\{\frac{(0.204*\eta)}{(\eta+\Pi_g)}*\ln(135-\Pi_g)\right\}^{0.5} \quad (4)
$$

$\varepsilon$ integrates the aspects that define the intensity of the environmental impact of a thermal power plant in one coefficient: the fuel composition, the combustion technology (in the pollution indicator) and the conversion efficiency.

The value of $\varepsilon$ is directly proportional to the plant’s efficiency, and is inversely proportional to the value of $\Pi_g$. Also, it varies between 0 and 1, similarly to the thermal plant’s efficiency. Ecologically speaking, $\varepsilon=0$ is considered to be an unsatisfactory situation, but $\varepsilon=1$ indicates the ideal situation (Cardu and Baica, 1999). The values of $\varepsilon$ follow the conditions below:

- For $\Pi_g = 0$ kg/MJ (in the case of hydrogen), $\varepsilon = 1$ for all $\eta$ values;
- For $\Pi_g = 134$ kg/MJ (sulfur), $\varepsilon = 0$ for all $\eta$ values;
- For $0$ kg/MJ $< \Pi_g < 134$ kg/MJ (other fossil fuels), $0 < \varepsilon < 1$ for all $\eta$ values.

3.1 Methodology application

In order to determine the ecological efficiency values for the thermal plants installed in Brazil, different fuels with their respective generation technologies are evaluated. The fuel characteristics are presented in Tables 5 and 6, as well as the pollution indicator, the carbon dioxide equivalent and the low calorific value. It must be highlighted that for the sustainable use of biomass (sugar cane bagasse), the net emissions of CO\textsubscript{2} are considered to be null.
Table 5: Characteristics of solid and liquid fuels – chemical composition is mass based (Cortez and Lora, 1997; Garcia., 2002; Nogueira and Lora, 2002).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Technology</th>
<th>η(%)</th>
<th>Chemical composition (%)</th>
<th>Πₗₕ</th>
<th>(CO₂)ₑ</th>
<th>Qi(MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>S</td>
<td>H₂</td>
<td>O₂</td>
</tr>
<tr>
<td>Diesel</td>
<td>Internal Combustion Engines</td>
<td>38</td>
<td>85.7</td>
<td>0.85</td>
<td>12.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Coal – CE4500</td>
<td>Steam turbine</td>
<td>41</td>
<td>46.29</td>
<td>2.01</td>
<td>3.06</td>
<td>0.95</td>
</tr>
<tr>
<td>Biomass (BIG/GT)</td>
<td>34</td>
<td>44.8</td>
<td>0.01</td>
<td>5.35</td>
<td>39.5</td>
<td>0.38</td>
</tr>
<tr>
<td>Biomass (TCE-80)</td>
<td>25</td>
<td>44.8</td>
<td>0.01</td>
<td>5.35</td>
<td>39.5</td>
<td>0.38</td>
</tr>
<tr>
<td>Biomass (BIG/GT)</td>
<td>70</td>
<td>44.8</td>
<td>0.01</td>
<td>5.35</td>
<td>39.5</td>
<td>0.38</td>
</tr>
<tr>
<td>Biomass (TCE-80)</td>
<td>33</td>
<td>44.8</td>
<td>0.01</td>
<td>5.35</td>
<td>39.5</td>
<td>0.38</td>
</tr>
<tr>
<td>Biomass (TCP-20)</td>
<td>28</td>
<td>44.8</td>
<td>0.01</td>
<td>5.35</td>
<td>39.5</td>
<td>0.38</td>
</tr>
</tbody>
</table>

a- Values of (CO₂)ₑ with control methods.
b- Value of N₂ for international fuel oil. (Garcia, 2002)
c- Biomass Integrated Gasification/ Gas Turbine - Electricity generation
d- Condensation Steam Turbine with Extraction, initial pressure 80 bars – Electricity generation
e- Counter Pressure Steam Turbine, initial pressure 20 bars.
f- Cogeneration

Based on the data presented in the table above, it is possible to calculate the ecological efficiency of the fuels that were considered (Table 7). It is called “Ecological Efficiency Critical Value” ε = 0.5, which is the minimal accepted from an ecological point of view (Cardu and Baica, 1999). This value was obtained from the idea of using a type of coal with a low calorific value and a high amount of sulfur as fuel, and its ecological efficiency would range about 0.5. Its use would not be recommended because of the large environmental impact caused by its combustion, for it releases great amounts of polluting gases.

Table 7: Characteristics of gaseous fuels – chemical composition is volume based (Garcia, 2002).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Technology</th>
<th>η</th>
<th>Chemical composition (%)</th>
<th>(CO₂)ₑ</th>
<th>Πₗₕ</th>
<th>Qi(MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>CH₄</td>
<td>C₂H₆</td>
<td>C₃H₈</td>
<td>C₄H₁₀</td>
</tr>
<tr>
<td>NG</td>
<td>Combined cycle</td>
<td>58</td>
<td>91.8</td>
<td>5.58</td>
<td>0.97</td>
<td>0.03</td>
</tr>
<tr>
<td>NG</td>
<td>Open cycle – GT</td>
<td>36</td>
<td>91.8</td>
<td>5.58</td>
<td>0.97</td>
<td>0.03</td>
</tr>
</tbody>
</table>

a- The values of (CO₂)ₑ were considered with control methods.

The ecological efficiency ε is calculated using the formula:

ε = \frac{\text{Q}_{\text{fuel}} - \text{Q}_{\text{desired}}}{\text{Q}_{\text{fuel}}}

where Q_{fuel} is the energy content of the fuel and Q_{desired} is the energy content of the desired product. The control technologies considered for the calculation of the ecological efficiency were the following (EPA):

- Combined cycle (CC) – Dry Low NOₓ Burners (DLNB) – 90%.
- Gas turbine (GT) – open cycle – Dry Low NOₓ Burners (DLNB) – 90%.
- Internal combustion engine (ICE) – Flue Gas Desulfurization (FDG) – 95% / SCR – 85% / Electrostatic Precipitator (ESP) – 99%.
- Steam turbine (ST) – Low NOₓ Burners (LNB) + Non-selective Catalytic Reduction (NSCR) – 65% / FDG – 95% / ESP – 99%.
- TCE – 80 – NSCR (50%) / ESP – 99%
- BIG/GT – DLNB - 90%.
- TCP-20 – ESP – 99%.

Table 7: Ecological efficiency of the studied technologies.

<table>
<thead>
<tr>
<th>Technologies</th>
<th>CC</th>
<th>GT</th>
<th>ICE</th>
<th>Coal ST</th>
<th>BIG/ GT</th>
<th>ST (TCE-80)</th>
<th>BIG/GT (cog.)</th>
<th>ST (TCE-80) (cog.)</th>
<th>ST (TCE-20) (cog.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε without control</td>
<td>0.991</td>
<td>0.988</td>
<td>0.688</td>
<td>0.431</td>
<td>0.601</td>
<td>0.466</td>
<td>0.734</td>
<td>0.518</td>
<td>0.487</td>
</tr>
<tr>
<td>ε with control</td>
<td>0.995</td>
<td>0.991</td>
<td>0.885</td>
<td>0.877</td>
<td>0.991</td>
<td>0.974</td>
<td>0.996</td>
<td>0.980</td>
<td>0.971</td>
</tr>
</tbody>
</table>
Figure 1 presents a comparison between the ecological efficiencies with and without pollutant removing methods. Figure 2 shows a relation between the pollution indication and the ecological efficiency. Figure 3 presents the advantages of the cogeneration using different generation technologies.
As noted in Figure 1 the ecological efficiency presents a considerable increase when pollutant control methods are used. It is possible to say that the technological development allows the environmental impacts of thermal generation to be considerably reduced once control methods are implemented, and that plants that present higher efficiencies also present higher ecological efficiencies. Figure 2 shows that, in general, the relation between ecological efficiency and the pollution indicator is the inverse, that is, the higher the ecological efficiency is, the lower the pollution indicator is and vice-versa. Finally, Figure 3 presents the advantages of using cogeneration, which result in higher ecological efficiencies, mainly when gaseous pollutant control methods are used.

4. CONCLUSIONS

It is possible to evaluate the environmental impacts of thermal power plants in an integral way by using the ecological efficiency parameter. Therefore, it is possible to state that:

- It is possible to achieve high ecological efficiencies by using highly efficient energy conversion advanced technologies;
- The use of atmospheric pollutant removing methods allows the attainment of acceptable values of ecological efficiency;
- For the air quality standards adopted in this study, one can observe that the use of natural gas together with advanced technologies, such as CC, constitutes an excellent option from an ecological point of view;
- Steam cycle thermal plants that use coal without control technologies do not reach a critical value of ecological efficiency;
- In Brazil, thermal plants using coal only use electrostatic precipitators as their control technology, and the emissions of SO$_x$ and NO$_x$ are not submitted to any sort of control. This way, the value of ecological efficiency using the ESP would be 0.707;
- The use of sugar cane bagasse for cogeneration in steam cycle installations with high parameters (8.0 MPa) and BIG/GT installations is characterized by ecological efficiency values of 0.974 and 0.991, respectively, considering electricity generation only. Considering the efficiencies of a cogeneration system, these will become 0.980 and 0.996, showing the advantages of this technology using pollutant control methods.
- Cogeneration can have a significant contribution towards the addition of energy efficiency in thermal power installation, increasing, this way, its ecological efficiency.

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6. References

Cardu, M., Baica, M., 1999, “Regarding a global methodology to estimative the energy-ecologic efficiency of
Cardu, M., Baica, M., 1999, “Regarding a new variant methodology to estimative globally the ecologic impact of
thermopower plants. Energy Conversion and Management; 40(14); pp 1569-75.
Cardu, M., Baica, M., 2000, “Regarding the energy ecologic efficiency of desulphurization and denox systems and
Manaus, 540 pp. (in Portuguese)
EPA (Environmental Protection Agency), 1995, “Compilation of Air Pollutant Emissions Factors”, AP-42, Fifth
Interciencia Publishing House, Rio de Janeiro. Published in Portuguese
43(14) pp 2553-67.
Publishing House, Rio de Janeiro. Published in Portuguese.
Publisher Fama, São Paulo. (in Portuguese)
energy resources in gas turbines”, ECN - Biomass, June;
Sydkraff, 2001, Värnamo - Demonstration Plant.

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