Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants

Marco Aurelio dos Santos\textsuperscript{a,c,*}, Luiz Pinguelli Rosa\textsuperscript{a}, Bohdan Sikar\textsuperscript{d},
Elizabeth Sikar\textsuperscript{b}, Ednaldo Oliveira dos Santos\textsuperscript{a}

\textsuperscript{a}IVIG/COPPE/UFRJ and Energy Planning Program/COPPE/UFRJ, Centro de Tecnologia, Bloco I, Sala 129, Cidade Universitária, 21945-970 Rio de Janeiro, Brazil
\textsuperscript{b}Construmaq Sao Carlos Ind. e Com. Ltda., Brazil
\textsuperscript{c}University of Grande Rio, Unigranrio—Environmental Program Studies, Brazil
\textsuperscript{d}Department of Hydraulics, University of Sao Paulo at Sao Carlos, Brazil

Available online 15 December 2004

Abstract

This paper presents the findings of gross carbon dioxide and methane emissions measurements in several Brazilian hydro-reservoirs, compared to thermo power generation.

The term ‘gross emissions’ means gas flux measurements from the reservoir surface without natural pre-impoundment emissions by natural bodies such as the river channel, seasonal flooding and terrestrial ecosystems. The net emissions result from deducting pre-existing emissions by the reservoir.

A power dam emits biogenic gases such as CO\textsubscript{2} and CH\textsubscript{4}. However, studies comparing gas emissions (gross emissions) from the reservoir surface with emissions by thermo-power generation technologies show that the hydro-based option presents better results in most cases analyzed.

In this study, measurements were carried in the Miranda, Barra Bonita, Segredo, Três Marias, Xingo, and Samuel and Tucuruí reservoirs, located in two different climatological regimes. Additional data were used here from measurements taken at the Itaipu and Serra da Mesa reservoirs.

Comparisons were also made between emissions from hydro-power plants and their thermo-based equivalents. Bearing in mind that the estimated values for hydro-power plants include emissions that are not totally anthropogenic, the hydro-power plants studied generally posted lower emissions than their equivalent thermo-based counterparts.

Hydro-power complexes with greater power densities (capacity/area flooded—W/m\textsuperscript{2}), such as Itaipu, Xingo, Segredo and Miranda, have the best performance, well above thermo-power plants using state-of-the-art technology: combined cycle fueled by natural gas, with 50% efficiency.

On the other hand, some hydro-power complexes with low-power density perform only slightly better or even worse than their thermo-power counterparts.

\textcopyright 2004 Elsevier Ltd. All rights reserved.

Keywords: Hydro-power; Thermo-power plants; Greenhouse gas; Power dam

1. Introduction

Last 2 decades several measurements of flux of CO\textsubscript{2} and CH\textsubscript{4} carried out in natural lakes and rivers at worldwide level showing important considerations on the role of water bodies’ contribution to the Greenhouse Effect.
Devol et al. (1988) measured the flow of CH₄ in areas flooded by the Amazon River at the beginning of the period of flooding. The average emissions found were 75 kg C/km²/day in flooded forests, 90 kg C/km²/day in lakes and 590 kg C/km²/day where there were floating plants. Another important point for comparison is the presence of carbon in the water, in the form of CO₂ and CH₄. High concentrations of CO₂ have been found in the water of flooded land, greater than the concentration of equilibrium with the atmosphere (Junk, 1985; Richey, 1982).

As lakes and rivers hydro-reservoirs produce biogenic gases through decomposing organic matter underwater. The bottom of the reservoir contains biomass that decomposes anaerobically, emitting principally CH₄ and N₂, and secondarily CO₂. In aerobic decomposition only CO₂ and N₂ are emitted.

At the end of 1990s the World Dam Commission was formed to provide a great synthesis of environmental and social implications of dams including the role of dams to enhance the Greenhouse Effect. The WCD recognized that dams are a source of greenhouse gases. In the study carried out in Brazil, gross GHG emissions from each of the selected reservoirs were assessed through sampling, with subsequent extrapolation of the findings to obtain a value for the total reservoir area.

However, this paper do not calculate natural emissions from soils and water before the impoundment as the approach conducted by Delmas et al. (2001) at Petit Saut Reservoir in French Guiana. The implications of our method was be that our calculations do not consider the net flux of dam reservoirs and our results would be greater because we do not discount the natural fluxes before the construction of the dam.

A wide variation in the intensity of the emissions was noted, indicating the influence of many different factors including temperature, measurement-point depths, wind system, sunlight, physical and chemical parameters of the water, composition of the biosphere, reservoir operations system and the local hydrological cycle which is directly related to external organic matter washed in from the soils and slopes of the watershed basin (surface and subsurface water).

For a given reservoir we developed a methodology for obtaining a representative average gas flux, taking spatial and temporal variations into account. A detailed explanation of this methodology is included in Rosa et al., 2002.

This makes it harder to separate anthropic emissions from emissions that would have occurred even without the dam. However, as it is impossible to calculate natural emissions by existing reservoirs, this methodology is applied only to plan reservoirs.

This paper is designed to provide input for the ongoing discussion comparing electricity produced from fossil fuels burned in thermo-power plants and the emissions by power dams, as factors contributing to the greenhouse effect.

### 2. Case studies in Brazil

Brazil has over 400 large and medium-sized power dams generating about 93% of its electricity, located between the Equator and latitude of approximately 30°S.

Working closely with Water Resources and Applied Ecology Center at the University of São Paulo (CRHEA/USP), the COPPE/UFRJ team carried out several studies on greenhouse gases emissions by hydro-power plants: in 1992–1993 at the Tucuruí, Balbina and Samuel power-dams in Amazonia; in 1997 through a joint experiment with UQAM au Montreal at the Curua-Una power dam in the Amazon Region; in 1997–1998 at the Serra da Mesa power dam; in 1998–1999 at the Itaipu power dam; in 1998–1999 at the Miranda and Três Marias hydro-power dams (Minas Gerais), as well as Barra Bonita (São Paulo), Segredo (Paraná), Xingó (Alagoas and Sergipe), Samuel

### Table 1

<table>
<thead>
<tr>
<th>Dam</th>
<th>Latitude</th>
<th>Biome</th>
<th>Power (MW)</th>
<th>Reservoir Area (km²)</th>
<th>Power Density (MW/km²) (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miranda</td>
<td>18°55’S</td>
<td>Savanna</td>
<td>390</td>
<td>50.6</td>
<td>7.71</td>
</tr>
<tr>
<td>Três Marias</td>
<td>18°13’S</td>
<td>Savanna</td>
<td>396</td>
<td>1,040</td>
<td>0.38</td>
</tr>
<tr>
<td>Barra Bonita</td>
<td>22°31’S</td>
<td>Atlantic forest</td>
<td>140.76</td>
<td>312</td>
<td>0.45</td>
</tr>
<tr>
<td>Segredo</td>
<td>25°47’S</td>
<td>Atlantic forest</td>
<td>1,260</td>
<td>82</td>
<td>15.37</td>
</tr>
<tr>
<td>Xingó</td>
<td>09°37’S</td>
<td>Scrub savanna</td>
<td>3,000</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>Samuel</td>
<td>08°45’S</td>
<td>Rain forest</td>
<td>216</td>
<td>559</td>
<td>0.39</td>
</tr>
<tr>
<td>Tucuruí</td>
<td>03°45’S</td>
<td>Rain forest</td>
<td>4,240</td>
<td>2,430</td>
<td>1.74</td>
</tr>
<tr>
<td>Serra da Mesa</td>
<td>13°50’S</td>
<td>Savanna</td>
<td>1,275</td>
<td>1,784</td>
<td>0.71</td>
</tr>
<tr>
<td>Itaipu</td>
<td>25°26’S</td>
<td>Atlantic forest</td>
<td>12,600</td>
<td>1,549</td>
<td>8.13</td>
</tr>
</tbody>
</table>
(Rondônia) and Tucuruí (Pará); and in 2001–2002 to develop a gas monitoring model for two selected power dams (Miranda and Xingó) (Rosa et al., 2002).

These studies took latitude, climate and specific vegetation into account, as well as the density of the biomass drowned by the power dams. Table 1 shows the technical and geographical characteristics of each reservoir studied.

3. Related works on power dams and GHG emissions

A report prepared for the World Commission on Dams (WCD) by Rosa and Santos (2000) that was included in the WCD—Final Report (2000a) prompted much controversy on this topic worldwide. At the moment, this quantification remains incomplete at the global level (Matvienko et al., 2001; Rosa and Santos, 2000; Rosa et al., 2002).

Studies completed so far seem to indicate that many different factors influence gas generation in power dams. Carbon dioxide and methane are produced during the decomposition of organic matter. In dams, the source of organic matter may be drowned pre-existing biomass, dissolved organic carbon and particulate organic carbon (DOC and POC) carried down from the watershed areas, as well as biomass generated within the dam itself.

At the oxic water level, CO$_2$ is produced through aerobic decomposition of DOC and POC, with methane oxidation generated at lower water levels. For organic matter in anoxic sediments, bacterial decomposition takes place through methanogenesis, resulting in CH$_4$ and CO$_2$.

Studies of natural eco-systems such as lakes and rivers in tropical regions present findings corroborating the fact that power dams produce biogenic gases, contributing to the greenhouse effect and its problems (Devol et al., 1988; Bartlett et al., 1993; Kelly and Stallard, 1994; Hamilton et al., 1995; Adams, 1996; Alvalá et al., 1999; Richey et al., 2002).

Recently, Richey et al. (2002) carried out a study to check the release of biogenic gases from rivers and flooded areas in Amazônia. These findings indicate that the outflow of CO$_2$ from rivers and flooded areas in the Central Amazon Basin (1.77 million km$^2$) constitutes an important carbon loss process of approximately $1.2 \pm 0.3$ Mg Ch$_{-1}$year$^{-1}$. This paper stresses that carbon originates from organic matter carried down from flooded upland forests, which then oxidizes and is released further downstream.

Richey et al. extrapolate these results to cover the entire Amazon Basin, noting that the flow-rate would be around 0.5 Gt C year$^{-1}$ higher than that of river-borne exports of organic carbon to the ocean.

More specifically, we present some information below that should be taken into account for GHG emissions by Brazilian power-dams.

Our studies (Rosa and Santos, 2000) extrapolating the measurement data at certain points on selected dates for each dam indicate that a small number of hydro-power projects may produce emissions higher than those of thermo-power plants;

Due to the variability within and among the dams, we do not feel properly qualified at the moment to generalize by applying the data from one hydro-power project to another, far less estimate the global contributions of these power dams.

4. Methodology

Data on CH$_4$ and CO$_2$ generation through organic decomposition in the flooded areas that constitute the dam are rather sparse and difficult to organize into a working body of information.

Two types of measurement were performed to cover ebullitive emissions (by bubbles) and diffusive gas exchanges at the water–air interface (Matvienko et al., 2001; Rosa and Santos, 2000; Rosa et al., 2002, 2003).

The equipment was taken by motorboat to the sampling location, where funnels suspended from pairs of plastic floats (volume: 2 l) trapped spontaneous rising bubbles. The funnel mouth diameter was 0.7 m, with the tip at an angle of 60°. The tip ended in a 20 mm polyamide piece over which a test tube or a larger collection vessel could be fastened. The collection vessels were originally filled with water.

Rising bubbles reaching the funnel mouth were channeled to the collection vessel where they accumulated over 24 h periods, after which they were harvested and, having noted the total collected volumes, they were taken to the laboratory for chromatographic analysis.

Gas exchanges at the water–air interface were evaluated by an equilibration method through which confined portions of air were allowed to partly equilibrate with the gas dissolved in the water during 5 and 10 min periods, using diffusion chambers.

The bubbles contained mainly methane (up to 97.7 mol%) while CO$_2$ release prevailed for diffusion (99.0%). A thermal conductivity gas chromatograph was used to analyze samples for CO$_2$. Methane was analyzed using a flame ionization detector.

In order to predict the future development of gas emissions a mathematical model was developed based on gas emission data.

It is also grounded on the supposition that part of the original biomass flooded by the dam decomposes in a relatively short period of time, dropping exponentially within a few years, while trunks and thick branches decompose slowly, their emissions adding to those the dam throughout its life-span.
Emissions of carbon dioxide and methane in each of the selected dams, whether through bubbles or water/air diffusive exchange, were assessed by sampling, with subsequent extrapolation of the findings in order to obtain a value for the dam. These emission intensities varied widely, due to the influence of several factors, including temperature and the parameters for the water, the biosphere and the operating system of the dam. There was a wide and apparently random variability (up to 140%) in the CH$_4$ findings for bubbles, with relatively uniform CO$_2$ emissions.

Comparisons were also made between emissions from power dams and their thermo-power counterparts. Bearing in mind that the estimated values for hydro-power plants include emissions that are not totally anthropogenic, the power dams studied generally posted lower emissions than their thermo-based equivalents.

The measurements taken in two-field surveys (1998 and 1999) consisted of collecting gas flow data, wind regimes, temperatures and pH of water in the reservoirs studied.

In order to reach an average for each reservoir as a whole based on the findings of experimental observations at only some points of the reservoir and some days of the year, extrapolation criteria had to be adopted.

Our experimental findings show strong links between the CH$_4$ emission rate by bubbles and the depth of the reservoir. This appeared for all reservoirs studied, even if not so clearly, for depths of zero to around 20 m. For other areas there is no emission by bubbles and diffusion is essentially uniform.

The findings from transport by bubbles and molecular diffusion are added together to obtain the total emissions from the dam for the period of time under analysis.

Gas fluxes by molecular diffusion are much greater than by bubbling. Around 99% of CO$_2$ is emitted into the atmosphere by diffusive flux. For methane, diffusion

### Table 2

Average gas flux from dams measured in the first field trip

<table>
<thead>
<tr>
<th>Dam</th>
<th>CH$_4$ by bubbles (mg m$^{-2}$ d$^{-1}$)</th>
<th>CO$_2$ by bubbles (mg m$^{-2}$ d$^{-1}$)</th>
<th>CH$_4$ by diffusion (mg m$^{-2}$ d$^{-1}$)</th>
<th>CO$_2$ by diffusion (mg m$^{-2}$ d$^{-1}$)</th>
<th>CH$_4$ by ebullitive and diffusive fluxes (mg m$^{-2}$ d$^{-1}$)</th>
<th>Range values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miranda</td>
<td>29.2</td>
<td>0.3</td>
<td>233.3</td>
<td>4981.3</td>
<td>4980</td>
<td>262.4</td>
</tr>
<tr>
<td>Tres Marias</td>
<td>273.1</td>
<td>3.5</td>
<td>55.3</td>
<td>-138.5</td>
<td>-142</td>
<td>328.2</td>
</tr>
<tr>
<td>Barra</td>
<td>4.8</td>
<td>0.2</td>
<td>14.4</td>
<td>6434.2</td>
<td>6434</td>
<td>19.2</td>
</tr>
<tr>
<td>Bonita</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Segredo</td>
<td>1.7</td>
<td>0.1</td>
<td>8.3</td>
<td>4789.1</td>
<td>4789</td>
<td>9.9</td>
</tr>
<tr>
<td>Xingó</td>
<td>1.9</td>
<td>0.01</td>
<td>28</td>
<td>9837.1</td>
<td>9837</td>
<td>29.99</td>
</tr>
<tr>
<td>Samuel</td>
<td>19.3</td>
<td>0.6</td>
<td>164.3</td>
<td>8087.6</td>
<td>8087</td>
<td>183.6</td>
</tr>
<tr>
<td>Tucurui</td>
<td>13.2</td>
<td>0.14</td>
<td>192.2</td>
<td>10,433</td>
<td>10,433</td>
<td>205.4</td>
</tr>
<tr>
<td>Itaipu</td>
<td>0.5</td>
<td>&lt;1</td>
<td>12.4</td>
<td>1205</td>
<td>1205</td>
<td>12.9</td>
</tr>
<tr>
<td>Serra da Mesa</td>
<td>111</td>
<td>1.9</td>
<td>10</td>
<td>1317.9</td>
<td>1316</td>
<td>121</td>
</tr>
</tbody>
</table>

5. Results of reservoirs measurement

Gas fluxes by molecular diffusion are much greater than by bubbling. Around 99% of CO$_2$ is emitted into the atmosphere by diffusive flux. For methane, diffusion
into the atmosphere is in the range of 14–90% of the total flux.

According to our measurements, flux intensity at reservoirs varies over time, but the variations appear to be modulated by a strong random component.

The coexistence of underwater CO₂ and CH₄ sources (organic matter such as detritus, dissolved carbon, aquatic plants, zooplankton, etc.) and sinks (photosynthesis, oxidation, etc.), whose activity is governed by a complex interplay of internal and external factors, results in this apparent randomness and explains the presence of extreme values. Tables 2 and 3 show the variability among various reservoirs. Tables 4 and 5 provide information on the sampling sites at each reservoir studied.

Table 6 gives the average findings for surveys measuring greenhouse gases emitted by nine power dams in Brazil.

6. Emissions comparison: power-dams × thermo-power plants

These findings allow power-dam emissions to be compared with those produced by thermo-power plants with equivalent capacities.

For these comparisons, the emissions by the equivalent thermo-power plants must be calculated and characterized as generating the same annual amount of...
energy as each power dams, burning different fuels and with technology efficiency levels that vary from steam turbines to coal, fuel oil/natural gas turbines and combined cycle.

The average amount of electricity generated was evaluated for a year’s operations by each hydro-power plant, multiplying its installed capacity in MW by an average capacity factor for Brazilian hydro-power plants of around 50% and the number of hours in the year (8760), resulting in the amount of generated energy expressed in MWh/year.

In order to calculate the amount of carbon emitted by thermo-power technology, the annual amount produced by hydro-power was multiplied by a carbon emission factor associated with each fuel, expressed in tC/MWh (Table 7) and divided by the average efficiency of each technology (Table 8).

These efficiency levels varied from 30% to 37%, for simple cycle powered by diesel oil, coal, natural gas or fuel oil, rising to 50% for combined cycle operations fueled by natural gas.

The calculation of emissions by thermo-power plants fueled by natural gas (largely methane) included fugitive emissions caused mainly by losses during fuel shipment and distribution operations. These losses were caused mainly by minor leaks throughout the entire distribution network, including gas pipelines, piping and other components.

Accidental leaks may also occur, as well as losses during maintenance operations or system maneuvers. According to data produced by Petrobras (1999), Brazil’s fugitive emissions are estimated at 4.7%.

Table 7
Data used thermo-power plant calculations

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Emission factor tC/TJ</th>
<th>Conversion factor MWh/TJ</th>
<th>Emission factor tC/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam coal</td>
<td>25.8</td>
<td>0.0036</td>
<td>0.9288</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>21.1</td>
<td>0.0036</td>
<td>0.7596</td>
</tr>
<tr>
<td>Diesel oil</td>
<td>20.2</td>
<td>0.0036</td>
<td>0.7272</td>
</tr>
<tr>
<td>Natural gas</td>
<td>15.3</td>
<td>0.0036</td>
<td>0.5508</td>
</tr>
</tbody>
</table>


Table 8
Efficiency ratings of technologies used by thermo-power plants

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Technology</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam coal</td>
<td>Simple cycle</td>
<td>37</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>Simple cycle</td>
<td>30</td>
</tr>
<tr>
<td>Diesel oil</td>
<td>Simple cycle</td>
<td>30</td>
</tr>
<tr>
<td>Natural gas</td>
<td>Simple cycle</td>
<td>30</td>
</tr>
<tr>
<td>Natural gas</td>
<td>Combined cycle</td>
<td>50</td>
</tr>
</tbody>
</table>

Schaeffer et al. (2001).


This percentage initially analyzes the global warming potential (GWP) of CH₄ compared to CO₂: 7.6 carbon mass units for 100 years (IPCC, 1996), which is reflected in a 27% increase in equivalent carbon emissions (CO₂).

Table 9 gives a brief comparison of emissions by power dams with an equivalent thermo-power plant, with power-dam emissions calculated at the average measurements recorded during the two sampling campaigns and extrapolated for each reservoir as a whole.

7. Final comments

This study concludes that although hydro-power is not a clean energy source in terms of atmospheric greenhouse emissions, these dams performed better than thermo-power plants in most cases analyzed. This indicates that they offer a feasible solution for reducing greenhouse gas emissions by the power sector, in comparative terms.

Some hydro-power complexes (Itaipu, Xingó, Segredo) emit very little carbon compared to their thermo-based counterparts; there are some intermediate power dams (such as Miranda), and others that actually emit more carbon, such as Tres Marias and Samuel for instance.

Accidental leaks may also occur, as well as losses during maintenance operations or system maneuvers. According to data produced by Petrobras (1999), Brazil’s fugitive emissions are estimated at 4.7%.

Table 8
Efficiency ratings of technologies used by thermo-power plants

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Technology</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam coal</td>
<td>Simple cycle</td>
<td>37</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>Simple cycle</td>
<td>30</td>
</tr>
<tr>
<td>Diesel oil</td>
<td>Simple cycle</td>
<td>30</td>
</tr>
<tr>
<td>Natural gas</td>
<td>Simple cycle</td>
<td>30</td>
</tr>
<tr>
<td>Natural gas</td>
<td>Combined cycle</td>
<td>50</td>
</tr>
</tbody>
</table>

Schaeffer et al. (2001).


This percentage initially analyzes the global warming potential (GWP) of CH₄ compared to CO₂: 7.6 carbon mass units for 100 years (IPCC, 1996), which is reflected in a 27% increase in equivalent carbon emissions (CO₂).

Table 9 gives a brief comparison of emissions by power dams with an equivalent thermo-power plant, with power-dam emissions calculated at the average measurements recorded during the two sampling campaigns and extrapolated for each reservoir as a whole.

7. Final comments

This study concludes that although hydro-power is not a clean energy source in terms of atmospheric greenhouse emissions, these dams performed better than thermo-power plants in most cases analyzed. This indicates that they offer a feasible solution for reducing greenhouse gas emissions by the power sector, in comparative terms.

Some hydro-power complexes (Itaipu, Xingó, Segredo) emit very little carbon compared to their thermo-based counterparts; there are some intermediate power dams (such as Miranda), and others that actually emit more carbon, such as Tres Marias and Samuel for instance.

It is important to stress that, for each case, the measurements merely quantify gross emissions in comparative terms, as the organic matter continually draining into the basin is not quantified for separation from the biomass drowned by the dam.

The comparative findings clearly indicate that the problem should be analyzed on a case-by-case basis, due to marked variations among power dams.

In addition to the type of calculations presented in this paper, further research into GHG emissions by power dams required, such as:

- Lower intra- and inter-dam uncertainty levels;
- A full life-cycle assessment should be covered by future studies, including emissions prior to the dam. Carbon cycle studies should be encouraged, in order to determine natural and anthropogenic carbon sources throughout the entire watershed area;
- Discussions and upgrading the GWP Index for comparing thermo-based and power dam emissions;
- Degassing emissions downstream from the turbines should be included.

Acknowledgements

We express our deepest gratitude to Eletrobras and the Ministry of Science and Technology for financing work and discussing important points in this paper with...
### Table 9
Comparison of emissions by power dams with an equivalent thermo-power plant

<table>
<thead>
<tr>
<th>Dam</th>
<th>Area (Km²)</th>
<th>Latitude</th>
<th>Capacity (MW)</th>
<th>Dam CH₄ emission index (kg/km²/d)</th>
<th>Dam CO₂ emission index (kg/km²/d)</th>
<th>Dam emissions (tC/year)</th>
<th>Coalᵣ, simple cycle (tC–CO₂/year)</th>
<th>Oilᵣ, simple cycle (tC–CO₂/year)</th>
<th>Dieselᵣ, simple cycle (tC–CO₂/year)</th>
<th>Gasᵣ, simple cycle (tC–CO₂/year)</th>
<th>Gasᵭ, combined cycle (tC–CO₂/year)</th>
<th>Merit-RI (thermo-emissions/hydro emissions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tucuruí</td>
<td>2430</td>
<td>3°45'S</td>
<td>4240</td>
<td>109.4</td>
<td>8475</td>
<td>2,602,945</td>
<td>4,661,873</td>
<td>4,702,228</td>
<td>4,501,659</td>
<td>4,330,284</td>
<td>2,598,170</td>
<td>1.79</td>
</tr>
<tr>
<td>Samuel</td>
<td>559</td>
<td>8°45'S</td>
<td>216</td>
<td>104.0</td>
<td>7448</td>
<td>535,407</td>
<td>237,492</td>
<td>239,547</td>
<td>229,330</td>
<td>220,599</td>
<td>132,360</td>
<td>0.44</td>
</tr>
<tr>
<td>Xingó</td>
<td>60</td>
<td>9°37'S</td>
<td>3000</td>
<td>40.1</td>
<td>6138</td>
<td>41,668</td>
<td>3,298,495</td>
<td>3,327,048</td>
<td>3,185,136</td>
<td>3,063,880</td>
<td>1,838,328</td>
<td>79.16</td>
</tr>
<tr>
<td>Serra da Mesa</td>
<td>1784</td>
<td>13°50'S</td>
<td>1275</td>
<td>51.1</td>
<td>3973</td>
<td>895,373</td>
<td>1,401,860</td>
<td>1,413,995</td>
<td>1,353,683</td>
<td>1,302,149</td>
<td>781,289</td>
<td>1.57</td>
</tr>
<tr>
<td>Três Marias</td>
<td>1040</td>
<td>18°13'S</td>
<td>396</td>
<td>196.3</td>
<td>1117</td>
<td>540,335</td>
<td>435,401</td>
<td>439,170</td>
<td>420,438</td>
<td>404,432</td>
<td>242,659</td>
<td>0.81</td>
</tr>
<tr>
<td>Miranda</td>
<td>50.6</td>
<td>18°55'S</td>
<td>390</td>
<td>154.2</td>
<td>4388</td>
<td>38,332</td>
<td>428,804</td>
<td>432,516</td>
<td>414,068</td>
<td>398,304</td>
<td>238,983</td>
<td>11.19</td>
</tr>
<tr>
<td>Barra Bonita</td>
<td>312</td>
<td>22°31'S</td>
<td>140.76</td>
<td>20.9</td>
<td>3985</td>
<td>137,341</td>
<td>154,765</td>
<td>156,105</td>
<td>149,447</td>
<td>143,757</td>
<td>86,254</td>
<td>1.13</td>
</tr>
<tr>
<td>Itaipu</td>
<td>1549</td>
<td>25°26'S</td>
<td>12,600</td>
<td>20.8</td>
<td>171</td>
<td>93,269</td>
<td>13,853,680</td>
<td>13,973,602</td>
<td>13,377,571</td>
<td>12,868,296</td>
<td>7,720,978</td>
<td>148.54</td>
</tr>
<tr>
<td>Segredo</td>
<td>82</td>
<td>25°47'S</td>
<td>1260</td>
<td>8.8</td>
<td>2695</td>
<td>23,497</td>
<td>1,385,368</td>
<td>1,397,360</td>
<td>1,337,757</td>
<td>1,286,830</td>
<td>772,098</td>
<td>58.96</td>
</tr>
<tr>
<td>Set of 9</td>
<td>23,518</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4,908,166</td>
<td>25,857,759</td>
<td>26,081,572</td>
<td>24,969,088</td>
<td>24,018,532</td>
<td>14,411,119</td>
<td>5.27</td>
</tr>
</tbody>
</table>

For natural gas, these emission factors include the 1.27 factor based on 4.7% fugitive losses and 7.6 GWP for methane.

ᵣCapacity of Power dams × 0.5 × 365 × 24 × CO₂ emission /fuel efficiency factor. A 50% incremental energy factor was used to include the increased total energy of the interconnected system from each power-dam.

ᵩIncludes CH₄ carbon (with GWP according to the IPCC, 1996) and CO₂ carbon: (CH₄ × 12/16 × 7.6 + CO₂ × 12/44) × 365/1000.

*CO₂ emission factor—coal, simple cycle: 0.9288 tC/MWh, with 37% efficiency rating.

*CO₂ emission factor—fuel oil, simple cycle: 0.7596 tC/MWh, with 30% efficiency rating.

*CO₂ emission factor—diesel oil, simple cycle: 0.7272 tC/MWh, with 30% efficiency rating.

*CO₂ emission factor—natural gas, simple cycle: 0.5508 × 1.27 tC/MWh, with 30% efficiency rating.

*CO₂ emission factor—natural gas, combined cycle: 0.5508 × 1.27 tC/MWh, with 50% efficiency rating.
us. We offer our thanks to Ronaldo Sérgio Monteiro Lourenço and Carlos Frederico da Silveira Menezes for important cooperation in the fieldwork.

References


Further reading


