GREENHOUSE GAS EMISSIONS FROM HYDROELECTRIC RESERVOIRS IN TROPICAL REGIONS

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Abstract. This paper discusses emissions by power-dams in the tropics. Greenhouse gas emissions from tropical power-dams are produced underwater through biomass decomposition by bacteria. The gases produced in these dams are mainly nitrogen, carbon dioxide and methane. A methodology was established for measuring greenhouse gases emitted by various power-dams in Brazil. Experimental measurements of gas emissions by dams were made to determine accurately their emissions of methane (CH_4) and carbon dioxide (CO_2) gases through bubbles formed on the lake bottom by decomposing organic matter, as well as rising up the lake gradient by molecular diffusion. The main source of gas in power-dams reservoirs is the bacterial decomposition (aerobic and anaerobic) of autochthonous and allochthonous organic matter that basically produces CO_2 and CH_4. The types and modes of gas production and release in the tropics are reviewed.

1. Introduction

A study by the Alberto Luiz Coimbra Institute at the Federal University of Rio de Janeiro (COPPE/UFRJ) in Brazil (Rosa et al., 2002) has shown that hydro-power complexes are not blameless in terms of greenhouse gas emissions.

Dams produce biogenic gases through decomposing organic matter, although additional studies are required to establish a better level of knowledge of this matter, while also reducing the uncertainties inherent to the findings available to date.

In the study carried out in Brazil, carbon dioxide (CO_2) and methane (CH_4) emissions by each of the selected dams were assessed through sampling, with subsequent extrapolation of the findings to obtain a value for the total reservoir area.

A wide variation in the intensity of the emissions was noted, indicating the influence of many different factors: temperature, measurement-point depths, wind

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systems, sunlight, physical and chemical water parameters, biosphere composition, and even dam operating systems.

An important point was the relatively low correlation between CO_2 emissions and the age of the dam, probably because the emissions are due not only to the decomposition of the pre-existing land-based biomass stocks, but also organic matter swept down from the upstream drainage basin (biomass and soil carbon, and possibly sewage and waste-water discharges as well), in addition to the organic matter – such as phytoplankton – produced in the lake itself.

This makes it harder to separate anthropic emissions from those that would have occurred even without the dam.

However, the CH_4 emissions reveal a correlation with the age of the dam, although less than expected from our preliminary studies.

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

2. Case Studies in Brazil

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

Working closely with the Water Resources and Applied Ecology Center at the University of São Paulo (CRHEA/USP), the COPPE/UFRJ team has carried out several studies on greenhouse gases emissions by hydro-power plants:

- 1992–1993 – research project with Eletrobrás on the Tucuruí, Balbina and Samuel Hydro-Power Complexes in Amazonia;
- 1997 – joint experiment with UQAM in Montreal at the Curua-Una Power-Dam in Amazonia;
- 1997–1998 – research project with Furnas Centrais Elétricas and Serra da Mesa Energia S.A. for the Serra da Mesa Hydro-Power Dam;
- 1998–1999 – research project with Itaipu Binacional for the Itaipu Hydro-Power Dam;
- 1998–1999 – research project with Eletrobrás and the Ministry of Science and Technology for the Miranda and Três Marias hydro-power projects (Minas Gerais), Barra Bonita (São Paulo), Segredo (Paraná), Xingó (Alagoas and Sergipe), Samuel (Rondônia) and Tucuruí (Pará);
- 2001–2002 – research project with the National Power Regulator – ANEEL to implement a gas monitoring project in two selected dams (Miranda and Xingó).

The studies took latitude, climate and specific vegetation into account, as well as the density of the biomass submerged by the dams. Furthermore, the neighboring

Table I
Technical characterization of reservoirs studied

Dam	Latitude	Biome	Power (MW)	Reservoir area (km^2)	Power density (W/m^2)
Miranda	18°55′ S	Savanna	390	50.6	7.71
Três Marias	18°13′ S	Savanna	396	1,040	0.38
Barra Bonita	22°31′ S	Atlantic Forest	140.76	312	0.45
Segredo	25°47′ S	Atlantic Forest	1,260	82	15.37
Xingó	09°37′ S	Scrub Savanna	3,000	60	50.00
Samuel	08°45′ S	Rain Forest	216	559	0.39
Tucuruí	03°45′ S	Rain Forest	4,240	2,430	1.74
Serra da Mesa	13°50′ S	Savanna	1,275	1,784	0.71
Itaipu	25°26′ S	Atlantic Forest	12,600	1,549	8.13

plant life also determines the type and quantity of carbon inflow reaching the dam downstream and how it maintains an even balance.

Table I and Figure 1 shows the technical and geographical characteristics of each dam studied.

3. Previous Findings

A Report prepared for the World Commission on Dams (WCD) by Rosa and Santos (2000) was included in the WCD – Final Report (2000a) and mentioned in the IRN (2002), prompting much controversy over whether hydro-power plants are blameless or not in terms of greenhouse gases emissions.

However, our findings do not allow us to conclude, as the IRN did, that greenhouse gases emissions by power-dams are higher than those from thermo-power plants generating equivalent amounts of electricity. At the moment, this quantification remains incomplete at the global level.

Through the studies completed so far, it seems that many different factors influence the gas generation process in power-dams.

Carbon dioxide and methane form during the decomposition of organic matter. In dams, the source of organic matter may be submerged pre-existing biomass, dissolved organic carbon and particulate organic carbon (DOC and POC) swept down from neighboring onshore 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 oxidization generated at lower water levels.

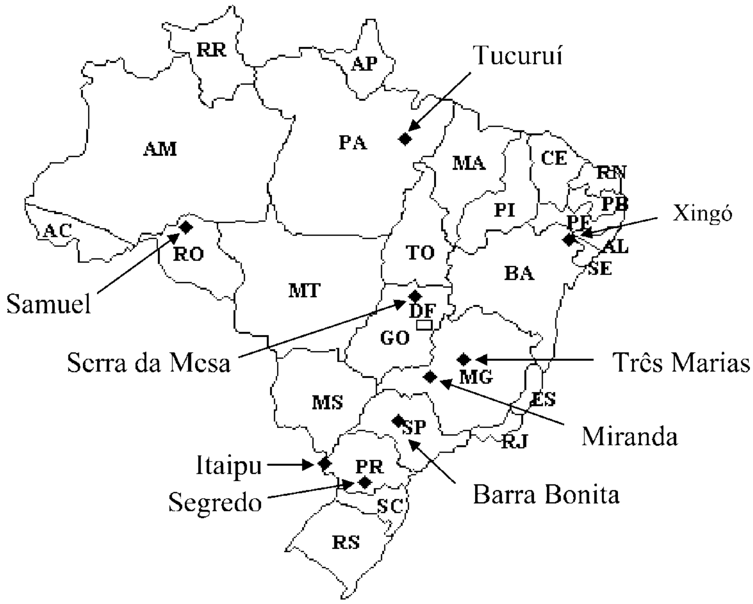

Figure 1. Geographical data on dams studied in Brazil.

For organic matter in anoxic sediments, bacterial decomposition takes place through methanogenesis, resulting in CH_4 and CO_2.

If the initial biomass inventory is known and the carbon processes are properly understood, gas flows may be calculated on a theoretical basis. However, at the moment reliable findings can be obtained only through gas exchange measurements in the field, taken at the air/water interface.

Studies of natural ecosystems, 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 (Shalard, 1980; Richey, 1982; Furch, 1984; Rickey et al., 1988, 1991; Devol et al., 1988; Bartlett et al., 1993; Kelly and Stallard, 1994; Hamilton et al., 1995; Adams, 1996; Alvald et al., 1998, 2001; Richey et al., 2002).

Methane emission studies in flooded tropical areas made tremendous progress, particularly during the 1980s in Amazonia and forested areas in Africa. Bartlett et al. (1993), took measurements in three different areas: flooded forests, water-bodies with no vegetation and water-bodies with plant cover. The average flow-rates varied from 7.5 mg CH_4 m^{-2} d^{-1} to 967 mg CH_4 m^{-2} d^{-1}, and the flooded areas averaged out at 200 mg CH_4 m^{-2} d^{-1}.

Recently, Richey et al. (2002) carried out a study to check the release of biogenic gases from rivers and flooded areas in Amazonia. 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 ± 0.3 Mg C $hectare^{-1}$ $year^{-1}$.

The Richey paper stresses that carbon originates in organic matter swept down from flooded upland forests, which then oxidizes and is released further downstream. This paper extrapolates these results to cover the entire Amazon Basin, noting that the flow-rate would be around 0.5 Gt C year^{-1}, demonstrating an order of magnitude higher than that of river-borne outflows of organic carbon to the ocean.

More specifically, we present below some information that should be taken into account for greenhouse gas emissions by Brazilian dams. These studies are not conclusive, although extrapolating the measurement data at certain points on selected dates for each dam indicates that a few of the 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 at the moment feel properly qualified to generalize by applying data on one hydro-power project to another, far less estimate the global contributions of these power-dams.

The findings indicate that there are some power-dams – such as Itaipu, Xingo and Segredo – that emit little carbon compared to their thermo-fueled counterparts, where the impact is some 137 times less than that of a plant fired by natural gas. Some mid-range hydro-power plants – such as Miranda – emit eleven times less carbon than a plant fired by natural gas, while other hydro-power plants emit up to twice the amount of carbon, such as Três Marias and Samuel. In each case, organic matter swept down steadily from the upstream basin was not quantified in order to separate it from the biomass submerged by the dam.

The compared findings indicate quite clearly that the problem should be analyzed on a case-by-case basis, as significant variations may occur from one hydro-plant to the next. Moreover, no investigation was undertaken of natural greenhouse gases emissions from these areas prior to filling the dams. Consequently, it is necessary to carry out an emissions assessment study prior to building a dam, so as to compare the emissions measured after its construction, and in order to identify the anthropic element in these emissions.

Looking at tropical dams in Brazil, it should be stressed that the IRN Report was based largely on a paper by Fearnside (2002) that focused on greenhouse gases emissions by the Tucuruí Hydro-Power Dam, whose findings include some discrepancies and many uncertainties. Initially, Fearnside (2002) addresses the issue of emissions by biomass decomposing aerobically in the dam above its waterline. The submerged biomass dies and decays through bacterial composition and termites. Although hard to confirm empirically, this is quite true.

The calculations by Fearnside (2002) outline a series of assumptions and associations, assuming that organic matter above the waterline decomposes at rates taken from earlier forest studies. We draw attention to the fact that Fearnside may be counting these gas emissions twice, as much of the matter that is subject to degradation – such as leaves and twigs – would already have been included in the initial biomass stock decomposing anaerobically on the lake bottom.

Immediately after power-dams are filled, the foliage of trees emerging from the water drops sharply, sinking to deeper portions of the reservoir (anoxic water levels). Meanwhile, thicker branches and tree-trunks containing ligno-cellulose may remain intact for perhaps even centuries, immune to attack by micro-organisms.

Second, the estimates by Fearnside (2002) are relatively pessimistic in terms of the tailrace and spillway emissions. The Tucuruí Hydro-Power Complex was filled in 1984, meaning that by 1991 it had been in existence for seven years.

In order to calculate the greenhouse gases emissions from the turbines, Fearnside (2002) used the data published in the work by Galy-Lacaux et al. (1997), based on measurements taken at the tailrace of the Petit Saut Dam in French Guiana, giving an average CH_4 concentration in the water of 7.5 mg CH_4 L^{-1}. This calculation is obtained by multiplying the flow-rate of the tailrace in 1991 by the average concentration at the water intake depth of the Tucuruí Dam (30 meters). The value obtained was 0.842×10^6 tons, scaled down by 6.7% to reach a figure of 0.785×10^6 tons.

The work of Galy-Lacaux et al. (1997) was carried out on completion of the dam (1994), and one year later (1995), while the Fearnside (2002) estimates were drawn up seven years after the Tucuruí Dam was filled (1991). This gap invalidates these estimates, as the measurements in French Guiana were taken during the peak outgassing period, immediately after the dam-wall was completed.

Another factor to be taken under consideration in the Fearnside (2002) estimates is that the measurements for the study in French Guiana were taken immediately above a type of water aeration unit located 100 meters downstream from the dam, which stirs up the water for forced aeration. This aeration unit eases the hydrostatic pressure, so that the gas in the water is released into the atmosphere faster. As there is no similar water aeration mechanism at Tucuruí, it does not seem appropriate to apply the situation at Petit Saut to Tucuruí.

Fearnside (2002) assumes that the effect of the water running through the turbine at Tucuruí is the same as that of the water running through the aeration unit at Petit Saut. However, this is not the case.

Our recent findings at the Miranda Dam (Minas Gerais) and the Xingó Dam (Alagoas and Sergipe) (Rosa et al., 2001), show that the effects on the water passing through the turbine are not analogous to water running through the aeration unit. The release of the methane, expressed in g m^{-2} just downstream from the dam, is only about 20% of the average for the dam, tending to drop even more downstream. In one case, the emission rate fell and a small absorption rate was in fact noted in the river about two kilometers downstream. The carbon dioxide release rate close to the dam downstream varied from 2,092 to 9,511 mg CO_2 m^{-2} d^{-1}, with an average of 4,296 mg CO_2 m^{-2} d^{-1}, (Rosa et al., 2001).

With regard to the concentration of dissolved gases downstream, we noted that the methane concentrations in the river some two kilometers away from the dam were equal to or less than those in the surface water of the dam; the concentrations of CO_2 hovered around the average CO_2 in the surface water of the dam. This leads to the conclusion that less methane is emitted downstream by area unit than by the dam. The CO_2 emissions immediately downstream from the dam averaged out at up to 4,296 mg CO_2 m^{-2} d^{-1}.

However, the heavy emissions area downstream covered less than one square kilometer, while power-dams usually cover thousands of square kilometers, as is the case with Tucuruí. This leads to the conclusion that these dams absorb far more than their downstream emissions, according to the measurements taken during these campaigns.

With regard to the emissions calculated for the Tucuruí spillway, Fearnside (2002) argues that the formation of aeration and the massive turbulence of the water running down the spillway immediately releases into the atmosphere all the methane dissolved in the water.

With no empirical support whatsoever, this statement is based on the assumption that all methane is released from the water as it pours down the spillway.

Fearnside (2002) used CH_4 concentration values measured in March 1989 by Tundisi (not published) and mentioned in Rosa et al. (1997), multiplied by an annual flow-rate of water through the spillway that he calculated, while applying a reduction factor of 40% to obtain a total figure of 0.535×10^6 tons of CH_4. This assumption is based on a worst-case assumption that all the methane is released into the atmosphere, with no on-site measurements taken at the spillway.

Our study leads to the conclusion that the intensity of gases emissions in a dam does not remain unchanged over time. There are fluctuations over periods whose duration also varies. However, the variation is modulated by a set of influences, with the main factors being: temperature, wind system, sunshine, physical and chemical water parameters and biosphere composition. For CO_2, these influences may blend in a way that indicates a trend for emission rates to be mildly affected by latitude, while dams at higher latitudes tend to post lower emission rates. However, this does not always occur, as is the case with methane, for instance.

In order to compare the effects of emissions by hydro-power plants (varying over time) with those produced by thermo-power plants that emit combustion gases at an almost constant rate throughout their useful lives, a solution must be found to the problem of how to compare emissions whose intensity varies at different times.

The Global Warming Potential (GWP) in the Intergovernmental Panel on Climate Change (IPCC) Reports is used to compare simultaneous emissions of different gases (IPCC, 1992, 1996).

Noting the misconceptions that occurred over the issue of global warming potential with the IPCC, COPPE/UFRJ prepared a methodology for generalizing global warming potential due to activities linked power generation (Rosa and Schaeffer, 1994, 1995; Rosa et al., 1996). This method compares the emissions of future hydro-power plants with those from their thermo-power counterparts that might be built instead of the hydro-power complexes. Based largely on biomass density data and the technical characteristics of the plants, it assumes that part of the biomass submerged by filling the dam in fact decomposes over a relatively brief period of

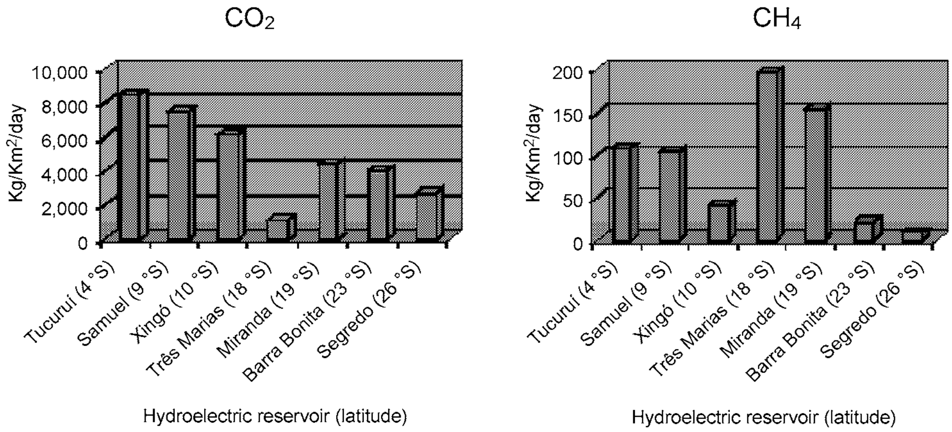

Figure 2. Emissions of CO_2 and CH_4 from power-dams studied, in kg/km^2/day.

time, decaying exponentially in just a few years, while thick branches and trunks remain, decomposing very slowly and adding their emissions to those of the lake, which will continue throughout its entire lifetime (Rosa et al., 1996).

The findings were used to draw up estimates guiding the selection of the hydropower plants to be studied. The worst case was that of Balbina, whose calculated emissions were worse than that of those of thermo-power plants generating the same amount of electricity, even those burning coal. The Tucuruí Complex emitted far less than an equivalent thermo-power plant, even when fueled by natural gas and combined cycle, according to these calculations (Rosa and Shaeffer, 1995; Rosa et al., 1996, 1997).

4. Findings on Power-Dams in Brazil

Other than the studies by COPPE/UFRJ for Eletrobrás in 1992–1993, FURNAS in 1997–1998 and Itaipu Binacional in 1998–1999, there are no reports in Brazil of on-site scientific studies to determine the total emissions of greenhouse gases (bubbles and molecular diffusion), through a systematic sampling program. Even at the international level, only a few such studies are known.

Recent measurements were carried out in the Miranda, Barra Bonita, Segredo, Três Marias, Xingó, Samuel and Tucuruí dams, located in two different climate systems.

Additional data were used from measurements taken at the Itaipu and Serra da Mesa dams (Figure 2).

These measurement methodologies were essentially the same in all cases. At each of the selected dams, emissions of carbon dioxide and methane were assessed by sampling, whether produced through bubbles or diffusive water-air exchanges, extrapolating these findings to obtain a value for each dam. The intensity of these emissions varied widely, due to factors that included temperature, measurement point depth, wind system, sunlight, physical and chemical water parameters, biosphere composition and the operating system of the dam in question.

An important observation was the relatively low correlation between emissions and the age of the dam, possibly because these emissions result not only from the decomposition of pre-existing terrestrial biomass, but also organic matter swept down the upstream drainage basin (carbon from biomass and soil, as well as sewage and wastewaters), in addition to organic matter produced in the dam itself (i.e., phytoplankton).

All this suggests greater difficulties in separating out the anthropogenic emissions (the purpose of this study) from emissions that would occur even without the dam.

Because of these factors, together with the limited number of dams studied, and the space and time constraints of the samples, these findings are somewhat uncertain. Bearing in mind that the estimated values for hydro-power plants include emissions that are not fully anthropogenic, the hydro-power plants studied generally posted lower emissions than their thermo-based counterparts. The best performances were posted by hydro-power plants with greater power densities (capacity $\times$ flooded area – W/m^2), such as Itaipu, Xingó, Segredo and Miranda, well above even that of thermo-power plants using state-of-the-art technology.

5. Closing Remarks and Conclusions

Various aspects of the estimates by Fearnside (2002) remain unclear, due to the use of data from the Petit Saut Dam in French Guiana, whose characteristics differ from those of the Tucuruí Hydro-Power Complex in Pará State, Brazil.

Furthermore, the sensitivity of these data is based on the values of two parameters for the CH_4 concentrations in water running down the spillways and through the turbines that have not yet been collected on-site.

Another factor to be taken into consideration in the Fearnside estimates (2002) is that the measurements in French Guiana were taken immediately above a type of water aeration unit, although this type of water aeration mechanism does not exist at Tucuruí, making it hard to apply the Petit Saut situation to the Tucuruí complex.

At every dam studied by COPPE/UFRJ in 2001/2002 (Rosa et al., 2002), carbon dioxide is emitted more through diffusion. However, as this gas forms part of the natural carbon cycle, CO_2 absorption by these water-bodies was noted in some measurements, through photosynthesis of the primary output of the dam. Methane is emitted by bubbling, as well as molecular diffusion.

At some dams, it was noted that the operating system may also influence gas emissions. Depending on how the plant is operated, the water level in its dam may drop rapidly, exposing its shallower branches to periodic colonization by land-based plants.

These regions show intensive methanogenesis due to the decomposition of this vegetation, particularly in the Três Marias and Samuel Dams.

An important observation was the relatively low correlation between the emissions and the age of the dam, possibly because these emissions are due not only to the decomposition of the pre-existing terrestrial biomass stocks but are also caused by organic matter swept down from the drainage basin upstream (carbon from biomass in the soil, as well as possible sewage and wastewater discharges), in addition to organic matter produced by the lake itself (i.e., phytoplankton).

Our studies also lead to the conclusion that hydro-power complexes do not produce atmospheric greenhouse gas emissions, as affirmed in environmental studies dating back to the 1970s and 1980s. Instead, power-dams emit biogenic gases such as CO_2, CH_4, N_2O and H_2S.

However, studies comparing gross gases emissions from dam surfaces with emissions by thermo-power generation technologies indicate that the figures for the hydro-power plants are better, in most cases.

These emissions vary according to the depth and distribution of the submerged biomass, and also alter over time, probably peaking rapidly soon after submersion, and then continuing at an unknown rate. Monitoring studies over lengthy periods should be encouraged in order to draw up an emissions behavior curve. The main scientific dispute is centered on extrapolating emissions measured at selected parts of the dam to the total area of the reservoir.

In general terms, it seems that the risk of greenhouse gases emissions could be reduced by:

(a) avoiding a low W/m^2 ratio (i.e., around 0.1);
(b) clearing biomass from the dam prior to flooding, although this measure must be analyzed from the economic and environmental standpoints.

Taking into consideration the recommendations issued by the Hydro-Quebec Meeting in Montreal (WCD, 2000b), the World Commission on Dams (WCD, 2000c) and the Rio GHG Working Team Report (Sikar et al., 2001), we feel the following aspects are important for further research into greenhouse gas emissions by power-dams, based on the points listed below:

(a) Taking the average values obtained so far, more research into greenhouse gas emissions by power-dams is required, particularly with regard to levels of uncertainty that should be reduced;
(b) Experimental measurements and assessments of specific locations provide only partial views, because dams vary widely from one place to another. However, these studies are necessary to provide data on the variability issue;
(c) The assessment of the complete lifecycle should be included in future studies, while also considering existing emissions prior to the dam being built. Carbon cycle studies should be encouraged in order to determine the origin of the carbon (natural and anthropogenic) in the total river-basin area;

(d) It is important to include a discussion of the role of the GWP index within the IPCC, comparing emissions by thermo-power plants and power dams;
(e) In addition to upgrading the measurement technology, we feel that funnels and static chambers are methodologies that have been standardized internationally and should be recommended for fresh studies, even if in parallel to other techniques;
(f) Future studies should include emissions caused through downstream release by the turbines;
(g) New measurements should be taken in order to capture the random data effect due to seasonal variations in gas emissions;
(h) A scientific network should be set up in order to encourage exchanges of data with comparisons of findings.

Blaming hydro-power plants for the environmental damages caused by their massive dams has long been a concern at COPPE/UFRJ, which carried out a study through the International Development Research Center (IDRC) in Canada that resulted in some publications (Rosa et al., 1988; Santos and Andrade, 1990; Rosa et al., 1995).

Subsequently, we became more concerned with the greenhouse effect, trying to convince Brazilian power utilities to support the measures implemented by the COPPE/UFRJ team.

It is necessary to avoid falling into the trap of the lobby of the unconditional supporters of the hydro-power plants, claiming that they are completely blame-free in terms of greenhouse gases emissions, which is today the official position of national gases inventories, while also avoiding the lures of the thermo-power and nuclear-power lobbies that are trying to blame higher emissions on power dams. Our approach has been to avoid exaggeration, including discussions with representatives of both sides.

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