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

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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_2 and CH_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, Xingó, 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^2), such as Itaipu, Xingó, 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.

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

1. Introduction

Last 2 decades several measurements of flux of CO_2 and CH_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.

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Devol et al. (1988) measured the flow of CH_4 in areas flooded by the Amazon River at the beginning of the period of flooding. The average emissions found were 75 kg C/km^2/day in flooded forests, 90 kg C/km^2/day in lakes and 590 kg C/km^2/day where there were floating plants. Another important point for comparison is the presence of carbon in the water, in the form of CO_2 and CH_4. High concentrations of CO_2 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 CH_4 and N_2, and secondarily CO_2. In aerobic decomposition only CO_2 and N_2 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 hydropower 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
Technical characterization of reservoirs studied

Dam	Latitude	Biome	Power (MW)	Reservoir Area (km^2)	Power Density (MW/km^2) (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
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

(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 oxidization 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 $1.2 \pm 0.3\,\mathrm{Mg\,C\,ha^{-1}\,year^{-1}}$. 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 $0.5\,\mathrm{Gt\,C\,year^{-1}}$ 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 reservoir for the period under analysis. The emissions rate was calculated on the basis of the data obtained in the experimental measurements, arriving at an average value for the two surveys of each reservoir. This value will be used for the extrapolation to a one-year period.

The sampling method differs from what is sometimes called the tower procedure, where the fluctuations in gas concentrations—in this case CO_2—are measured in the air at a certain height above the water surface while at the same time charting the horizontal and vertical wind speed. Based on the measurements carried out under several wind direction conditions, the dam emissions can be calculated. We did not use this method because—in parallel to high costs and the lack of portability of the equipment—the tower covers only a small area compared with the total area of the reservoir.

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

For bubbled emissions that do not occur at greater depths, a weighted average was created for the entire reservoir; and for diffusive emissions (which were found to be independent of depth), the simple mean of the measured values was used.

With the quantification of the emissions of the reservoirs studied in this paper, a comparison is made with emissions for hypothetical thermo-power plants of the same capacity. This allows the quantification of the relative advantages of hydro-power plants compared to these virtual thermo-power plants, run by a variety of fuels and technologies.

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

Table 2
Average gas flux from dams measured in the first field trip

Dam	Gas flux by bubbles ($mg\,m^{-2}\,d^{-1}$)		Gas flux by diffusion ($mg\,m^{-2}\,d^{-1}$)		Sum of ebullitive and diffusive fluxes ($mg\,m^{-2}\,d^{-1}$)		Range values			
	CH_4	CO_2	CH_4	CO_2	CO_2	CH_4	CO_2 bubbles	CO_2 diffusion	CH_4 bubbles	CH_4 diffusion
Miranda	29.2	0.3	233.3	4981.3	4980	262.4	0.03–0.5	16–61,182	0.002–175.6	20–4,572
Tres Marias	273.1	3.5	55.3	−138.5	−142	328.2	0.006–8.3	33–(−10,060)	0.001–1205	0.9–241
Barra Bonita	4.8	0.2	14.4	6434.2	6434	19.2	0.008–0.77	1614–33,424	0.002–21	3.1–29
Segredo	1.7	0.1	8.3	4789.1	4789	9.9	0.002–2	0.0001–46,857	0.004–29	0.002–64
Xingó	1.9	0.01	28	9837.1	9837	29.99	0.004–0.06	29–89,203	0.01–15	3.3–142
Samuel	19.3	0.6	164.3	8087.6	8087	183.6	0.004–3.5	2313–16,345	0.0001–67	4.9–2375
Tucuruí	13.2	0.14	192.2	10,433	10,433	205.4	0.002–0.96	1314–142,723	0.01–106	0.03–2.889
Itaipu	0.5	<1	12.4	1205	1205	12.9	0.01–0.74	−2646–7980	0.01–3.04	1.39–47
Serra da Mesa	111	1.9	10	1317.9	1316	121	0.03–2.2	−630.90–5900	5.5–645.3	−9.3–366

Table 3
Average gas flux measured in the second field trip

Dam	Gas flux by bubbles ($mg\,m^{-2}\,d^{-1}$)		Gas flux by diffusion ($mg\,m^{-2}\,d^{-1}$)		Sum of ebullitive and diffusive fluxes ($mg\,m^{-2}\,d^{-1}$)		Range values			
	CH_4	CO_2	CH_4	CO_2	CO_2	CH_4	CO_2 bubbles	CO_2 diffusion	CH_4 bubbles	CH_4 diffusion
Miranda	18.5	0.2	27.4	3796	3796	45.9	0.01–0.87	223–41,358	0.03–72.6	2.19–168.2
Três Marias	55.9	4.01	8.4	2373	2369	64.3	0.01–23.3	168–7346	0.04–402.5	0.66–70.75
Barra Bonita	3.1	0.05	19.5	1537	1537	22.6	0.002–0.19	83–20,391	0.0004–15.48	5.1–59.3
Segredo	1.9	0.03	5.7	601	601	7.6	0.02–0.25	165–16,218	0.01–15.4	2.14–14.59
Xingó	19.6	0.09	30.6	2440	2440	50.2	0.0004–1.9	341–17,239	0.78–407.3	3.54–92.9
Samuel	13.6	0.4	10.8	6808	6807	24.4	0.01–1.2	2200–24,283	0.07–37.6	6.13–17.16
Tucuruí	2.5	0.07	10.9	6516	6516	13.4	0.03–0.5	457–32,291	0.92–21.2	4.44–28.53
Itaipu	0.6	$<<1$	7.9	−864	−864	8.5	0.001–0.009	−4061–(−120)	0–1.9	0.9–57.30
Serra da Mesa	66.3	1.5	39.2	3973	3972	105	0.03–4.9	−5360–5903	0.2–337	−6048–10,178

Table 4
Characterization of sampling process in the first field trip

Dam	Number of sites visited		Number of samples	
	Funnel	Chamber	Funnel	Chamber
Miranda	8	5	9	23
Três Marias	4	5	12	23
Barra Bonita	4	7	12	15
Segredo	3	6	12	25
Xingó	2	6	7	19
Samuel	5	9	7	20
Tucuruí	5	4	10	23
Itaipu	4	5	12	27
Serra da Mesa	5	5	8	25

Table 5
Characterization of sampling process in the second field trip

Dam	Number of sites visited		Number of samples	
	Funnel	Chamber	Funnel	Chamber
Miranda	3	4	12	36
Três Marias	5	4	11	25
Barra Bonita	8	13	10	21
Segredo	3	3	12	36
Xingó	4	5	9	24
Samuel	2	7	6	19
Tucuruí	2	8	6	20
Itaipu	3	6	6	12
Serra da Mesa	3	8	12	11

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 CO_2 and CH_4 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 shows 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.

Table 6
Average results of two sampling field trips

Hydroelectric dam	Average of the two surveys			
	$Kg/km^2/day$		t/year	
	CO_4	CO_2	C–CH_4	C–CH_2
Miranda	154.15	4388	2135	22,104
Três Marias	196.28	1117	55,880	115,650
Barra Bonita	20.89	3985	1784	123,779
Segredo	8.79	2695	197	22,000
Xingó	40.09	6138	659	36,663
Samuel	104.02	7448	15,918	414,430
Tucuruí	109.36	8475	72,749	2,050,051

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

Fuel	Emission factor tC/TJ	Conversion factor MWh/TJ	Emission factor tC/MWh
Steam coal	25.8	0.0036	0.9288
Fuel oil	21.1	0.0036	0.7596
Diesel oil	20.2	0.0036	0.7272
Natural gas	15.3	0.0036	0.5508

Source: IPCC (1997).

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

Fuel	Technology	Efficiency (%)
Steam coal[a]	Simple cycle	37
Fuel oil[a]	Simple cycle	30
Diesel oil[a]	Simple cycle	30
Natural gas[b]	Simple cycle	30
Natural gas[b]	Combined cycle	50

[a]Schaeffer et al. (2001).
[b]Neto and Tolmasquim (2001).

This percentage initially analyzes the global warming potential (GWP) of CH_4 compared to CO_2: 7.6 carbon mass units for 100 years (IPCC, 1996), which is reflected in a 27% increase in equivalent carbon emissions (CO_2).

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.

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Table 9
Comparison of emissions by power dams with an equivalent thermo-power plant

				Average of two campaigns			Emissions by equivalent thermo-power plant[b]					Merit-RI (thermo-emissions/hydro emissions)				
Dam	Area (Km^2)	Latitude	Capacity (MW)	CH_4 emission index ($kg/km^2/d$)	CO_2 emission index ($kg/km^2/d$)	Dam emissions[a] (tC/year)	Coal[c], simple cycle (tC–CO_2/year)	Oil[d], simple cycle (tC–CO_2/year)	Diesel[e], simple cycle (tC–CO_2/year)	Gas[f], simple cycle (tC–CO_2/year)	Gas[g], combined cycle (tC–CO_2/year)	Coal, simple cycle	Oil, simple cycle	Diesel, simple cycle	Gas, simple cycle	Gas, comb. cycle
Tucuruí	2430	3°45′S	4240	109.4	8475	2,602,945	4,661,873	4,702,228	4,501,659	4,330,284	2,598,170	1.79	1.81	1.73	1.66	1.00
Samuel	559	8°45′S	216	104.0	7448	535,407	237,492	239,547	229,330	220,599	132,360	0.44	0.45	0.43	0.41	0.25
Xingó	60	9°37′S	3000	40.1	6138	41,668	3,298,495	3,327,048	3,185,136	3,063,880	1,838,328	79.16	79.85	76.44	73.53	44.12
Serra da Mesa	1784	13°50′S	1275	51.1	3973	895,373	1,401,860	1,413,995	1,353,683	1,302,149	781,289	1.57	1.58	1.51	1.45	0.87
Três Marias	1040	18°13′S	396	196.3	1117	540,335	435,401	439,170	420,438	404,432	242,659	0.81	0.81	0.78	0.75	0.45
Miranda	50.6	18°55′S	390	154.2	4388	38,332	428,804	432,516	414,068	398,304	238,983	11.19	11.28	10.80	10.39	6.23
Barra Bonita	312	22°31′S	140.76	20.9	3985	137,341	154,765	156,105	149,447	143,757	86,254	1.13	1.14	1.09	1.05	0.63
Itaipu	1549	25°26′S	12,600	20.8	171	93,269	13,853,680	13,973,602	13,377,571	12,868,296	7,720,978	148.54	149.82	143.43	137.97	82.78
Segredo	82	25°47′S	1260	8.8	2695	23,497	1,385,368	1,397,360	1,337,757	1,286,830	772,098	58.96	59.47	56.93	54.77	32.86
Set of 9			23,518			4,908,166	25,857,739	26,081,572	24,969,088	24,018,532	14,411,119	5.27	5.31	5.09	4.89	2.94

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

[a]Includes CH_4 carbon (with GWP according to the IPCC, 1996) and CO_2 carbon: $(CH_4 \times 12/16 \times 7.6 + CO_2 \times 12/44) \times 365/1000$.

[b]Capacity of Power dams $\times$ 0.5 $\times$ 365 $\times$ 24 $\times$ CO_2 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.

[c]CO_2 emission factor—coal, simple cycle: 0.9288 tC/MWh, with 37% efficiency rating.

[d]CO_2 emission factor—fuel oil, simple cycle: 0.7596 tC/MWh, with 30% efficiency rating.

[e]CO_2 emission factor—diesel oil, simple cycle: 0.7272 tC/MWh, with 30% efficiency rating.

[f]CO_2 emission factor—natural gas, simple cycle: 0.5508 $\times$ 1.27 tC/MWh, with 30% efficiency rating.

[g]CO_2 emission factor—natural gas, combined cycle: 0.5508 $\times$ 1.27 tC/MWh, with 50% efficiency rating.

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