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Tropical Hydropower in the Clean Development Mechanism: Brazil's Santo Antônio Dam as an example of the need for change

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Running head: **Hydropower in the CDM**

Policy relevance:

Hydroelectric dams have become major recipients of CDM funding, and the case examined here provides a concrete example of a widespread global problem. The CDM "pipeline" now has 2049 dams in different stages of the approval process. These dams are not additional, as they are being built at a rapid rate by countries such as China, India and Brazil independent of any subsidy for supposed mitigation benefits. The countries that purchase the credit generated by dams can emit more greenhouse gases without their being offset by genuine mitigation. The limited funds available for mitigation are also wasted on subsidizing dams that would be built anyway. In addition, tropical dams emit greenhouse gases despite CDM regulations allowing zero emissions to be claimed by many dams (including the case examined here).

ABSTRACT

When carbon credit is granted for projects that would occur irrespective of any subsidy based on mitigation of global warming, the projects generate "hot air," or credit without a real climate benefit. This is the case for tropical hydroelectric dams, which are now a major destination for funds under the Kyoto Protocol's Clean Development Mechanism (CDM). The countries that purchase the credit generated by dams can emit more greenhouse gases without their being offset by genuine mitigation. The limited funds available for mitigation are also wasted on subsidizing dams that would be built anyway. Tropical dams also emit substantially more greenhouse gases than are recognized in CDM accounting procedures. Tropical hydroelectric emissions are also undercounted in national inventories of greenhouse gases under the United Nations Framework Convention on Climate Change, giving them a role in undermining the effectiveness of as-yet undecided emission limits. Brazil's Santo Antônio Dam, now under construction on the Madeira River, provides a concrete example indicating the need for reform of CDM regulations by eliminating credit for hydroelectric dams.

Keywords: Amazonia; dams; global warming; greenhouse gas emissions; hydroelectric dams; methane; mitigation

1 Dams in the Clean Development Mechanism

1.1 Hydropower's role in the CDM

Hydroelectric dams can be subsidized by sales of carbon credit based on the supposition that they replace fossil-fuel powered thermoelectric plants that would otherwise be supplying electricity if the Kyoto Protocol's Clean Development Mechanism (CDM) were not granting carbon credit to hydropower. Hydroelectric dams are an increasingly important form of mitigation under the CDM, accounting for 10% of the credits issued so far but currently representing 26% of the expected issuance of credits from projects in the "pipeline" for funding (UNEP Risø Centre 2013). The CDM "pipeline" is an online database (http://cdmpipeline.org/cdm-projects-type.htm) on projects (both registered and not) with information collected from the United Nations Framework Convention on Climate Change (UNFCCC) by the United Nations Environmental Programme's Risø Centre. The Risø Centre is independent of the UNFCCC and its mechanism (the CDM) for funding mitigation projects in developing (non-Annex I) countries. As of 13 July 2013, 1943 hydroelectric projects had been "registered" (approved) by the CDM Executive Board, totaling 235.9 million Certified Emissions Reductions, or CERs [tons of CO_2e, or "CO_2-equivalent," the total of all greenhouse gases, such as methane (CH_4), expressed as amount of carbon dioxide (CO_2) that would have the same impact on global warming, in this case over a 100-year period; "ton" = Mg)] (UNEP Risø Centre 2013). Most (83.4%) of the projects submitted are eventually approved: of 2330 projects that either had a decision rendered or had been withdrawn, 83.4% had been registered, 0.4% had been withdrawn, 14.5% had been rejected by the validator (the "designated operational entity," or DOE), and only 1.7% had been rejected by the Executive Board (2.0% of those that reached the Executive Board for review).

The CDM pipeline (not counting rejected projects) totals 2049 dams claiming emissions reductions totaling 115 million CERs (UNEP Risø Centre 2013). China is the leading country in the CDM hydropower pipeline with projects totaling 59.7 million CERs annually in 1374 dams, followed by India with 12.7 million CERs in 243 dams and Brazil with 12.6 million CERs in 111 dams. "Large" dams (> 15 MW installed capacity by the CDM definition) accounted for 50.1% of the projects and 86.4% of the CERs as of March 2013, and the annual amount of expected carbon credit totaled 381.9 million CERs per year (Chu 2013). This amount of CO_2 equivalent is equal to 104.2 million tons of carbon per year, approximately equal to Brazil's annual emission from fossil fuels.

1.2 Emissions from tropical dams

Water in tropical reservoirs normally stratifies, either in whole or in part, leaving anoxic water at the bottom such that organic matter in the sediments forms methane (CH_4) rather than CO_2 (see review of emissions in the supplementary online material, Appendix A). Methane has greater impact on global warming per ton as compared to CO_2, and the relative weight attributed to methane affects the impact of hydroelectric dams as compared to fossil fuels, which essentially release only CO_2 (Fearnside 1997). Methane has a great impact on an instantaneous basis, but the average molecule of this gas only remains in the atmosphere for approximately 10 years, while CO_2 has a modest instantaneous impact but the average molecule remains for slightly over 100 years. The time horizon used for the comparison (and/or any discounting for time) therefore affects the relative weight attributed to methane in converting to "CO_2 equivalents" (CO_2e). Various atmospheric feedbacks included (or not) in climate models also affect this comparison. Until 2012 the CDM used 21 as the global warming potential (GWP) for methane, meaning that each ton of this gas has the same effect on global warming as 21 tons of CO_2 over a 100-year time horizon with no discounting for time. This was based on the IPCC's 1995 Second Assessment Report (Schimel et al. 1996). The CDM has now adopted 25 as the GWP of methane for use until 2017 based on the IPCC's Fourth Assessment Report (Forster et al. 2007).

The Fifth Assessment Report, released in September 2013, contains substantial changes affecting the impact of dams. While the GWP of methane increases to 28 if calculated in the same way as in previous reports, that is with a 100-year time horizon and with no feedbacks in the climate models, inclusion of feedbacks now known to exist in the real atmosphere increases the value to 34, and if a time horizon of 20 years is used instead of 100 years this value increases to 86 (Myhre et al. 2013). The latter value effectively quadruples the impact of dams as compared to virtually all published estimates (including those of this author). The 20-year time horizon is critical to policies aimed at containing global warming within the limit of 2°C above pre-industrial temperatures that was adopted at Copenhagen in 2009 by the UNFCCC as the definition of "dangerous" interference with the climate system (Decision 2/CP.15). We do not have 100 years to take effective measures to contain global warming, and rapid reduction of methane emission is a necessary part of any strategy to remain with in the 2°C limit (Shindell et al. 2012). Mitigation options such as tropical dams that have heavy impacts on global temperature increase in the next few decades cannot be considered "green," even if they show a net benefit if calculated from a vantage point a century in the future.

1.3 Undercounting hydropower emissions in the CDM

A CDM regulation allows zero emissions to be claimed if the power density (the ratio of installed capacity to reservoir area) is over 10 W/m^2 (EB23, Annex 5). However, a high power density does not result in zero emissions. A high power density means that the area of the reservoir is small relative to the installed capacity; the small area means that emissions through the reservoir surface (from bubbling and diffusion) will be smaller than in a large reservoir, but not zero. Water flow in "run-of-river" hydropower projects can be sufficient to prevent stratification in the main portion of their relatively small reservoirs. However, tributaries and bays can stratify, resulting in some methane emission (e.g., the Santo Antônio Dam example discussed in this paper).

Countries with high potential gains from CDM projects have played a disproportionate role in Executive Board decisions (Flues et al. 2008). Brazil played a key role in the CDM's decision to allow dams with power densities over 10 W/m^2 to claim zero emissions, which was based on an unpublished submission by Marco Aurelio dos Santos and Luiz Pinguelli Rosa, the former head of Eletrobrás (CDM Methodologies Panel 2006). This submission also proposed the low emission of 100 g CO_2/kWh attributed to dams in the 5-10 W/m^2 range. This submission was also the key to further lowering the limit for CDM eligibility from 5 to 4 W/m^2, and for lowering the assumed emission for dams in the 4-10 W/m^2 power-density range from 100 to 90 g CO_2/kWh. Both the 100 and the 90 g CO_2/kWh values refer only to bubbling and diffusion from the reservoir surface and are gross underestimates of hydropower impact because these values ignore the main sources of methane release: the turbines and spillways (e.g., Fearnside 2004; Fearnside and Pueyo 2012). The submission by dos Santos and Rosa, entitled "Options for Monitoring Emissions of GHGs: Providing Thresholds and Criteria for Hydroelectric Reservoirs" cited in the CDM's decision does not appear on the UNFCCC website. The CDM Executive Board has refused to divulge the document on the grounds that it was "not fully approved and only some elements of it were used," but suggested that it could be obtained from the report's authors "if" they were not under a confidentiality agreement (Sethi 2014). Meanwhile the authors refused to divulge the report on the grounds that it had been contracted under just such a confidentiality agreement from the CDM Executive Board itself (dos Santos 2014).

Despite these refusals, there is little doubt as to the content of the report, since the same issues are covered in various contemporaneous publications by its authors. One may deduce that this 2006 submission does not include downstream emissions (either those from the turbines or from the river below), since the authors omitted all such emissions from their other estimates (e.g., dos Santos et al. 2009; see Fearnside 2011). Similarly, one can also deduce that emissions from the reservoir surface (the only emissions source that would have been included) were based on mathematical errors that reduced the estimates by a factor of three (e.g., dos Santos et al. 2008; see Pueyo and Fearnside 2011). The Executive Board (EB) session that approved these changes was described by a participant as follows: "In the EB session, though, José Miguez from Brazil (the new EB chair) suggested that these were in fact very, very conservative figures and that 4 W/m^2 and 90 g/kWh would still be very conservative. Jean-Jacques Becker, the (outgoing) Meth Panel [CDM Methologies Panel] chair, did a rather poor job of defending the Meth Panel's figures, no one else had any expertise, so Miguez' suggestion got adopted" (Sterk 2006).

Another regulation favoring approval of dams involves calculation of reservoir area for the purpose of computing power density, which is the installed capacity in Watts divided by area in square meters. A June 2004 clarification approved by the Executive Board (EB15) allows a smaller reservoir area to be used in calculating power density (W/m^2) for purposes of taking advantage of a CDM criterion allowing zero emission to be claimed if the power density is greater than 10 W/m^2. The assumption is that water over the "river course" is not emitting methane. Unfortunately, this water can also emit methane, as shown by numerous studies that have measured reservoir surface fluxes at a variety of monitoring points in Amazonian reservoirs (see publications cited above). When a reservoir floods a river's course, the depth of the water increases and its velocity slows, which can allow the water column to stratify thermally and create anoxic conditions at the bottom, thus resulting in methane production. Methane-rich water from stratified bays and tributaries can also move into the area over the main channel, with the methane being released through the surface there. This is true either from the perspective of the common-sense definition of "river course" as the river channel that is covered by water year-round, or a relaxed definition (used in the Santo Antônio carbon project) that adds to this the floodplain that is normally flooded during the high-water period.

1.4 Additionality

CERs from the CDM contribute to global warming if credit is granted for mitigation projects that are not "additional" to what would have happened without the projects, as required by the Kyoto Protocol (UNFCCC 1997, Article 12, Paragraph 5). "Additionality" means that a project, such as a dam, would only exist because of the sale of carbon credits. If credit granted to dams is non-additional, the CDM hydro pipeline projects will allow this amount of carbon dioxide (381.9 million tons/year) to be emitted to the atmosphere by the countries that purchase the CERs without any real offsetting of the emissions by the CDM projects. These projects would also consume a growing share of the money that the world has for combatting global warming; the credit for dams in the CDM pipeline is expected to be worth over US$1 billion per year ["billion" =10^9], considering the US$3.65 per ton CO_2e price for CERs in mid-2008 (Ecopart 2011). Note, however, that CER prices have since crashed due to lack of progress in negotiations on the post-Kyoto regime and due to over-allocation of permits in the European Union Emissions Trading Scheme, which has a strong influence on the price of CERs generated by the CDM (Barrieu and Fehr 2011). One must assume that countries will eventually take on substantial commitments to reduce emissions under the UNFCCC, creating demand for carbon credit and causing prices to recover. If funds are given to projects that are not additional, the logical result is that fewer mitigation projects are undertaken of other types with a real benefit for climate.

CDM projects justify their claims that the projects would be financially unattractive by using additionality tests in one of two categories permitted under CDM rules: "investment tests" and "barrier tests." Investment tests compare the proposed project with other more carbon-intensive projects to show that the proposed project is less financially attractive than competing investments in the absence of CERs, while barrier tests seek to show that some impediment, such as a technological hurdle or a prevailing practice, would (unless overcome with funds from CERs) prevent implementation of the proposed project but would not block implementation of at least one alternative (e.g., du Monceau and Brohé 2011). Barrier tests have allowed many non-additional projects to be approved, particularly in India (e.g., Michaelowa and Purohit 2007; Schneider 2007; du Monceau and Brohé 2011). Investment tests, such as the one used by Santo Antônio, allow projects to claim additionality by showing that a calculated internal rate of return (IRR) is lower than a "benchmark" (minimum acceptable) IRR value chosen by the project. The IRR is the discount rate that results in the net present value of the project being zero. While IRR calculations can easily be manipulated (Fearnside 2013a), the behavior of the investors offers an unambiguous demonstration of non-additionality that all people can understand, whether or not they have the knowledge or patience to follow IRR calculations. The burden of proof for additionality rests with the proponents: there is no need to "prove" that a project is not additional. The CDM Executive Board apparently believes that building a dam before CDM support is obtained does not constitute evidence of non-additionality; this has the appearance of revealing bias in favor of approving projects regardless of their true additionality. The damage that ignoring investor behavior does to the CDM's credibility has a cost for global efforts to mitigate climate change that goes beyond the impact of emissions that occur from non-additional carbon credit sold by the project.

1.5 Sustainable development

Although Article 12 of the Kyoto Protocol, which created the CDM, specified that all projects must contribute to "sustainable development" (UNFCCC 1997), this potential safeguard against damaging environmental and social consequences of mitigation projects was greatly reduced by a later decision that "sustainable development" would be defined and judged by each country for itself, rather than following an international standard. Any project receiving a Letter of Approval (LoA) from the host country's Designated National Authority (DNA) is presumed to represent sustainable development. Brazil's negotiators were a key force in this decision: Brazil's priority at Kyoto in 1997 and for several years thereafter was focused on defending "the right to development and to make domestic choices regarding environmental sustainability measures" (Cole 2012). After submission to the CDM, designated operational entities (DOEs), better known as "validators," inspect projects and attest to the validity of claims, including contributions to sustainable development. This has not prevented approval of projects with major impacts, Brazil's Jirau Dam providing a recent example (Fearnside 2013a). The CDM's contribution to sustainable development is controversial (Appendix B). In the case of Brazil, proposed CDM projects, in practice, are not subject to any effective screening based on sustainable development (Appendix B).

2 A concrete example: The Santo Antônio Dam

2.1 The Santo Antônio Hydropower Project

The Santo Antônio Dam, under construction since 2008, is nearing completion on the Madeira River in the state of Rondônia in the southwestern portion of Brazil's Amazon region (8° 48'4.0" S; 63° 56'59.8" W)(Figure 1). The dam is being built and operated by Santo Antônio Energia, a consortium of FURNAS, Odebrecht, CEMIG, Andrade Gutierrez and Caixa FIP. The Madeira is a major Amazon tributary that drains parts of Brazil, Bolivia and Peru. When complete, in its initially approved configuration, the dam will have an installed capacity of 3150.4 MW with 44 bulb turbines; the first turbine began commercial operation in February 2012 and the remaining turbines are being installed at a rate of approximately one per month. The current configuration is expected to be completed in 2015 at a cost of US$9.3 billion (HydroWorld 2012). Although the dam is considered to be run-of-river, the barrage rises to a height of 55 m above the river bed; initially (prior to losses to sedimentation) the reservoir has a water depth of 46.3 m at the dam.

[Figure 1 here]

On 2 July 2013 permission was granted to raise the water level by an additional 0.8 m (from 70.5 m to 71.3 m above mean sea level; the original proposal was for a water level of 70 m); The 71.3-m level would allow six additional turbines to be installed totaling 420 MW (Tavares and Fariello 2013). This makes the dam's mitigation claim even less likely to be additional, since higher water level means that the dam generates more power, making it more profitable without the CDM than it would be under the specifications used in the CDM proposal's Project Design Document (PDD). However, even with the present 70.5-m level a record streamflow in 2014 caused severe flooding along the shores of the reservoir, including cutting the BR-364 Highway that connects the state Acre to the rest of Brazil. This lateral flooding would have been aggravated by the reservoir, since the rise in water level began at a higher elevation than would have been the case in the natural river (Fearnside 2014a). The impacts of the 2014 flood make it less likely that Santo Antônio Energia will be able to raise the reservoir level to 71.3 m without significant political opposition. The social and environmental impacts of the dam led to intense opposition from environmental and human-rights groups during and after the licensing process (Fearnside 2014b).

The Santo Antônio carbon project was approved (registered) by the CDM Executive Board in November 2013, retroactive to 28 December 2012; the retroactive official date makes the carbon credit valid for the European Union Trading Scheme, which had established a cutoff at the end of 2012. Granting CERs to Santo Antônio under the CDM will allow purchasers of these certificates to release 51 million tons of CO_2-equivalent (CO_2e) into the atmosphere elsewhere in the world. The purpose of the present examination of the Santo Antônio project is to extract lessons from this example regarding the CDM's regulations on hydroelectric projects, not to judge whether this particular project conforms to current regulations.

2.2 Emissions from the Santo Antônio Dam

The treatment of Santo Antônio's emissions in the PDD is reviewed in Appendix C. The PDD claims zero emissions from the reservoir (the only emissions pathway currently considered by CDM methodologies) based on the project's calculated power density. Emissions from other sources, such as decay of trees killed in the reservoir, downstream emissions, and construction of the dam and transmission line are not considered.

The amount of greenhouse-gas emission from Santo Antônio is very uncertain, since a full study has not yet been done (especially of downstream emissions). However, some measurements of CH_4 fluxes and of concentrations in the water and air were made in February 2012 (Grandin 2012; Hällqvist 2012). The environmental impact study (EIA) contains information relevant to CO_2 emission from the biomass in the flooded area and from construction of the dam and the transmission line, which is used in Appendix D to produce estimates of greenhouse gas emissions over the ten-year period of the carbon project.

The EIA contains estimates of the areas of each vegetation type and land use, as well as biomass estimates for the different vegetation types. These can be used, together with complementary information, to calculate the carbon stock in the flooded area. The ten-year period of the project is a reasonable time to assume that this biomass would decay, releasing its carbon as CO_2 (e.g., Barbosa and Fearnside 1996). The company has buried some of the tree biomass in shallow pits; this would slow carbon release, but probably not prevent its occurrence on a decadal time scale. Aside from downstream emissions, deforestation is the largest component of the project's emissions impact, with slightly over half of the non-downstream total (Appendix D, Tables S1 and S4).

Emissions from construction of the dam can be estimated from the quantities of steel, cement and other materials (Appendix D, Table S2). The quantities of materials used in constructing a hydroelectric dam are very much greater than those for an equivalent gas-fired power plant. An estimate for an equivalent gas-fired plant is included based on the steel in the turbines (Appendix D, Tables S3 and S4). Construction emissions represent 14% of Santo Antônio's impact excluding downstream emissions (Appendix D, Table S4). The choice of a time horizon assumes that ten years is a reasonable time over which to allocate construction emissions. This is a political and ethical decision, not a scientific one. The hydroelectric industry is anxious to have all comparisons be done on a 100-year basis with no discounting for time (e.g., Fearnside 1996, Goldenfum 2012); this would make hydroelectric dams appear relatively more attractive on various grounds, but runs counter to the interests of society in avoiding dangerous levels of global warming (e.g., Fearnside 2002).

Transmission line construction emissions can be estimated conservatively based on materials used, and ignoring other sources of emission (Appendix D, Table S2). Only half of the construction emissions are attributed to Santo Antônio, the other half being attributable to Jirau.

The carbon project counts the electricity produced at the point where it enters the Integrated National System (SIN) at a junction only 5 km from the dam. In reality, the vast majority of the electricity will be used in São Paulo after passing over a 2362-km line built to service the Madeira Dams. The project considers transmission loss to the junction with the SIN as only 3.2% (Santo Antônio Energia S.A. 2011, p. 34). However, Brazil's average loss in transmission is 20% (Rey 2012), and the very long transmission line to São Paulo, one of the longest in the world (Moreira 2013), suggests that losses would be greater than the national average. Not only is the transmission line omitted from the PDD's emission calculations, it also affects the amount of carbon credit claimed. Because the PDD claims credit based on the number of megawatt-hours at the point of delivery to the SIN, the amount of electricity reaching São Paulo would in reality be at least 20% less. If a gas-fired plant were used to replace the dam, it would be built near the city where the electricity is used, thus eliminating transmission loss. A gas-fired power plant's CO_2 emissions that are theoretically being eliminated by the dam would therefore be at least 20% less than claimed.

Flux measurements at the downstream sites were not possible due to excessive turbulence for use of the floating chambers. However, a very rough estimate of emission is possible based on the observed CH_4 enrichment of the air (detailed in Appendix D). The estimate involves uncertain information regarding the dimensions of the air mass to which the concentration enrichment values apply and the wind direction that, together with the wind speed, determines the rate at which the air over the river is renewed. These are based on average values, and could have been different at the time of the measurement. The measurement itself could always be atypical. Nevertheless, reasoning from the best information available, downstream emission represents 34.5% of the total if included in the computation for the 70.5-m water level (Appendix D). With downstream emissions at this level included, impact of the hydroelectric project's emissions range from 30% to 59% of the baseline scenario emissions, depending on the GWP used to convert CH_4 to CO_2e (Appendix D, Table S3). Both the downstream and upstream estimates assume that the values used, which were measured in the dam's first year after filling, apply to the full period of 10 years. This is uncertain, as reservoirs have emissions that oscillate over the annual cycle and that usually trend downwards over the first ten years (by widely varying amounts). A positive feature is Santo Antônio's management plan with a constant water level, albeit subject to variations such as the 2014 floods. A negative factor is the Madeira's large load of allochthonous carbon. A summary of Santo Antônio's emissions compared to supplying the same amount of power to São Paulo from gas-fired thermal plants is given in Table 1.

[Table 1 here]

Even if one gives no consideration to downstream emissions because of their high uncertainty, the remaining emissions total ranges from 27% to 43% of the emission from the baseline scenario for producing the same amount of electricity (Appendix D, Table S4). The emission is not "negligible," even when this major potential source of methane is ignored.

2.3 Non-additional carbon

The Project Design Document calculates a benefit of 51,464,028 CO_2e over 10.5 years (June 2012 – December 2022) (Santo Antônio Energia S.A. 2011, p. 35). Sale of this amount of carbon credit will contribute to further climate change if it is not additional.

The PDD justifies additionality by calculating the project's internal rate of return (IRR) without revenues from sale of carbon credit, and then comparing this value to a benchmark that is claimed to represent a minimum IRR that would be considered profitable (Appendix E). The Santo Antônio project opted for the Weighted Average Cost of Capital (WACC) method (average of cost of debt and cost of capital), which is one of two allowable indices for investment tests. The WACC is a benchmark representing project IRR rather than equity IRR, which is represented by the other permitted method, the Capital Assessment Pricing Model (CAPM) that was used, for example, for the Jirau Dam's CDM project. The benchmark (WACC) calculated for Santo Antônio was 10.35% and the calculated IRR without carbon credit was 5.63% (Santo Antônio Energia, SA 2012, pp. 14 and 16).

Some measure of common sense is required. Half of the WACC value calculated in the PDD is the cost of debt (calculated to be 3.39%), and the other half is the cost of capital, which is calculated at 17.31%. The latter value represents an equity IRR that serves as an indication of the profitability of the venture from the point of view of an investor. Few companies or investors can expect to make a return on investment of 17% per year, after taxes, over and above inflation and sustained over a period of ten years. The rationale for being allowed to claim that such a high return is necessary to make Santo Antônio attractive relies on a series of adjustments, representing supposed risks such as "Brazil country risk." While the series of adjustments in the computations may legitimize the practice in legal terms under current CDM regulations, they do not lead to decisions that make sense from the standpoint of combatting global warming. If the benchmark is too high, then projects that would happen anyway will be classed as "additional" and granted undeserved carbon credit.

The clearest indicator that the behavior of companies investing in the project does not match the calculated unprofitability of the venture without carbon credit is that the companies were willing to invest massive sums before the carbon project was even submitted, let alone approved. The probability of a CDM hydropower project being rejected, if calculated from the point of first submission, is 16.6% (see Section 1.1), which would be a high risk of losing the vast sums invested. In addition, the market for CERs crashed, with prices falling by over 70%, before many of the major investments were made, indicating additional risk that the price would not recover to the 2008 values used in the PDD. This would represent another major inhibitor if the project were really as unprofitable as the PDD claims without revenues from sale of CERs. The Occam's razor conclusion is that companies invested in the project with full expectation of making a profit without any additional help from the CDM, and none of the 51 million tons of CO_2-equivalent claimed is additional.

2.4 Environmental licensing

The PDD says of the environmental licensing that "This process consisted of 64 public meetings with the participation of 2000 people from the local communities that inhabit the area of direct influence of the hydroelectric plant" (Santo Antônio Energia S.A. 2011, pp. 46-47). It neglected to say anything about the content of those meetings, namely that virtually 100% of what was said was highly critical of the dam (e.g., Baraúna and Marin 2011). The livelihoods of the local population had depended heavily on the Madeira River's extraordinary fish resources, which have now been largely sacrificed for the Santo Antônio and Jirau Dams (see Fearnside 2014b).

The PDD form asks for "conclusions and all references to support documentation of an environmental impact assessment undertaken in accordance with the procedures as required by the host Party" (Santo Antônio Energia S.A. 2011, p. 47). Santo Antônio's PDD answers this by stating that "The project has all required environmental licenses issued by IBAMA" and listing the licenses (Santo Antônio Energia S.A. 2011, p. 47). Not mentioned are the multiple irregularities in the licensing process. The gravest was replacement of the head of the licensing sector of IBAMA (Brazilian Institute for the Environment and Renewable Natural Resources) just before the preliminary license was approved (the previous sector head had supported his technical staff in declining to approve the license). The new head of the licensing department was then promoted to head IBAMA as a whole, and approved the installation license in that capacity. These approvals overrode the technical staff of IBAMA, which had taken formal positions against approval of both the preliminary license (Deberdt et al. 2007) and the installation license (Brazil, IBAMA 2008). The licensing and impacts of the Madeira River dams are reviewed in detail elsewhere (Fearnside 2013b, 2014b,c).

2.5 Environmental and social impacts

Readers of the section of the PDD on environmental and social impacts (Santo Antônio Energia S.A. 2011, pp. 42-47) will have little idea of the severity of the impacts of the Santo Antônio Dam. The PDD even claims that "the Project will have an overall positive impact on the local and global environments" (Santo Antônio Energia S.A. 2011, p. 47). Unfortunately, the dam will have multiple negative impacts, including blockage of the migration of the giant catfish of the Madeira (*Brachyplatatystoma rouxeauxii* and *Brachyplatystoma platynemum*), which, until now, have been a vital economic resource not only in Brazil's state of Rondônia but also in Peru and Bolivia (e.g., Barthem and Goulding 1997). Prior to the dams, these fish ascended the Madeira River in a mass migration each year to breed in the headwaters of tributaries to the Madeira in Peru and Bolivia; the larvae then drifted down the Madeira to grow to their adult size in the Amazon River. Fish passages installed in the Santo Antônio and Jirau Dams have not been successful in attracting the ascending adult catfish, since the instinct of the fish is to follow the main current of the river. The Santo Antônio dam will also affect floodplain (*várzea*) lakes that are important fish-breeding sites downstream of the dam (not included in the EIA). The reservoir will release methylated mercury and destroy the livelihoods of the human population that has traditionally depended on the

Madeira River (Fearnside 2014b). The Madeira River dams, including Santo Antônio, are surely among the most controversial hydroelectric projects in the world today because of their impacts and because of the history of their licensing.

3 The global significance of Santo Antônio

The case of the Santo Antônio Dam carbon project has important implications for the world. Clearly it is "just" one dam, but it is added to the documented cases where carbon projects for tropical dams have been approved by the CDM despite being of questionable additionality. By its nature, the question of whether "all" tropical dams are non-additional, or the more relevant question of whether tropical dams should be treated as if all were non-additional, is approached through inductive reasoning – not by deduction from a universal principle. The two other hydropower carbon projects examined in Amazonia: Teles Pires (Fearnside 2012) and Jirau (Fearnside 2013a) are non-additional. Environmental activists have compiled less-detailed information on a long list of dams around the world, suggesting that non-additionality is very generalized, including in China and India (Yan 2013). A study of CDM projects in China and India has shown multiple ways that benchmarks have been manipulated to allow approval of non-additional projects (Haya 2009).

The decisions to which this information is relevant are policy decisions. As such, they are decisions that must be made, and this is done based on the best information available, rather than only on information meeting a criterion such as a statistical significance at the 5% level. In fact, most policy decisions, such as the choice of economic measures to contain inflation or increase employment, are based on information with levels of uncertainty much higher than those regarding the climate benefits (or lack thereof) associated with granting carbon credit to tropical dams. Delaying action on a halt to such credit on the grounds of excessive uncertainty is, in fact, an endorsement of the practice. Every day that nothing is changed a decision is being made to do nothing. The theoretical possibility of some dams being additional does not justify continuing to grant CDM funds to tropical dams (Fearnside 2013a). Santo Antônio being a large, run-of-river dam, represents a good choice of what should be a model project from the point-of-view of emissions per MWh, but, on closer examination, this benefit is found to be less than claimed.

Every tropical dam does not have to be non-additional for it to be the best decision to halt carbon credit for these dams. Carbon credit is a tool in the fight against global warming – not an entitlement to which companies or governments have any sort of moral right. If, in practice, granting credit to dams is doing more harm than good, or even if truly additional dams were frequent enough to result in a modest net benefit but using funds to subsidize dams has less gain for climate than would spending the money on a different category of mitigation measure, then the credit for dams should be discontinued immediately. The Santo Antônio carbon project adds one more case pointing to this as the logical conclusion.

4 Conclusions

The example of the Santo Antônio Dam shows that, in practice, CDM regulations award credit to dams that are not additional to what would occur without the subsidy. The credit granted for such dams therefore allows the countries purchasing the credit to emit greenhouse gases without a corresponding real offset. In addition, tropical hydroelectric dams themselves emit more greenhouse gases than are recognized in CDM procedures. Thus, the Santo Antônio example adds to a growing body of evidence supporting the conclusion that the practice of granting carbon credit to tropical dams should be halted immediately.

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Figure legend

Fig. 1. Locations mentioned in the text.

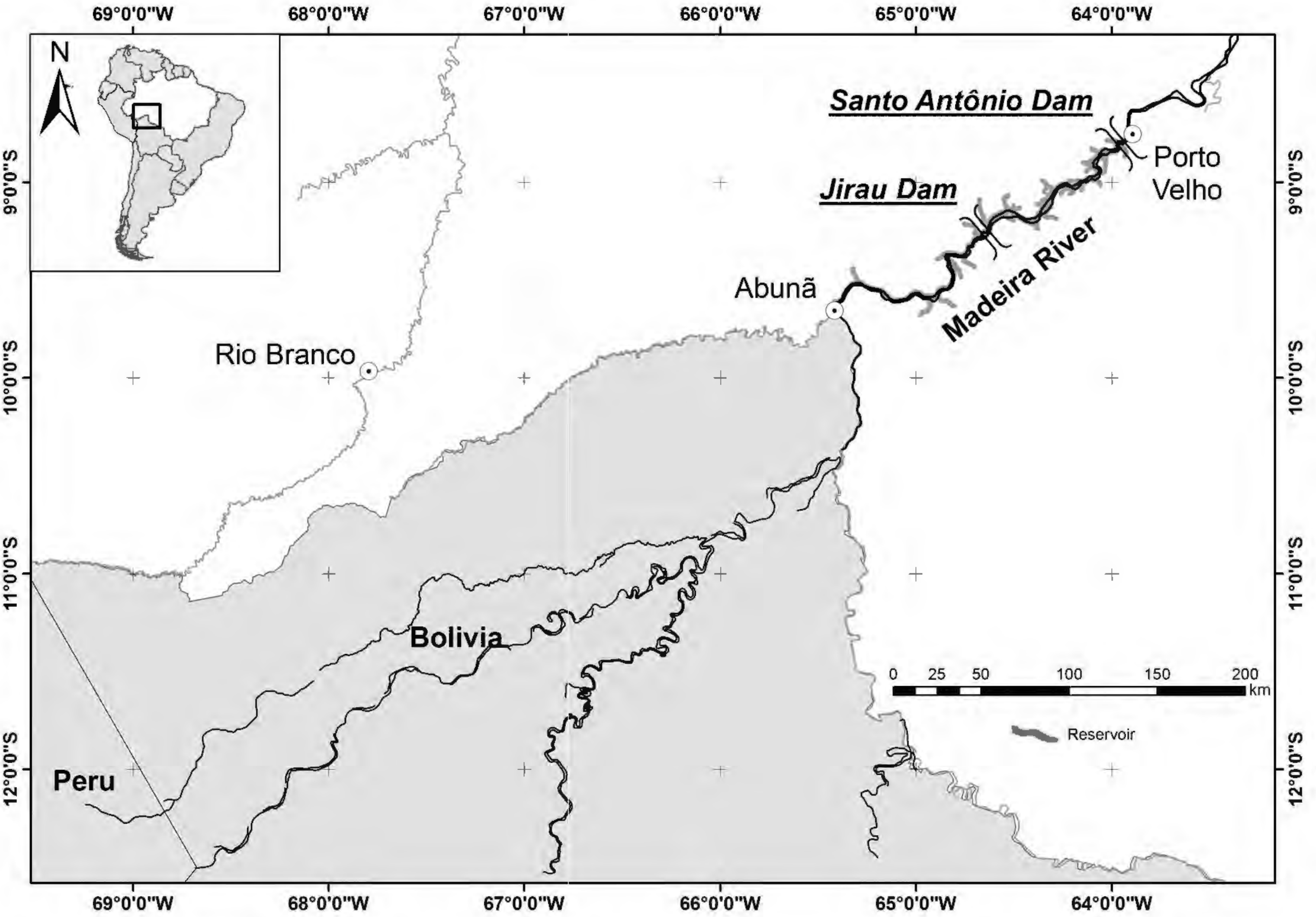
Table 1: Summary of estimated emissions from Santo Antônio compared to baseline emissions

	Estimated emission			Source in Supplementary Online Material
	GWP=25 (t CO_2e)	GWP=34 (t CO_2e)	GWP=86 (t CO_2e)	
Dam construction CO_2 emissions	1,542,836	1,542,836	1,542,836	Tables S1 & S3
Dam deforestation CO_2 emissions	6,368,215	6,368,215	6,368,215	Tables S1 & S3
Transmission line construction CO_2 emissions[a]	191,075	191,075	191,075	Tables S1 & S3
Transmission line deforestation CO_2 emissions	252,137	252,137	252,137	Tables S1 & S3
Dam methane emissions[b]	12,729,868	14,305,086	23,406,345	Table S3
Santo Antônio project total	21,084,131	22,659,349	31,760,608	Table S3
Gas-fired baseline construction	2,158	2,158	2,158	Table S3
Gas-fired baseline operation	51,464,027	51,464,027	51,464,027	Table S3
Gas-fired baseline total	51,466,185	51,466,185	51,466,185	Table S3
Santo Antônio emission per MWh (t CO_2-e)[c]	0.08	0.10	0.16	Table S3
Gas-fired baseline emission per MWh (t CO2-e)	0.27	0.27	0.27	Table S3

[a] Portion attributed to Santo Antônio only.

[b] Upstream+ downstream emission, 10-year project total.

[c] Emission per MWh delivered to São Paulo.


69°0'0"W
68°0'0"W
67°0'0"W
66°0'0"W
65°0'0"W
64°0'0"W
N
Santo Antônio Dam
Porto Velho
Jirau Dam
Madeira River
Abunã
Rio Branco
Bolivia
Peru
0
25
50
100
150
200
km
Reservoir
9°0'0"S
10°0'0"S
11°0'0"S
12°0'0"S

17 December 2014

Supplementary Online Material

Tropical Hydropower in the Clean Development Mechanism: Brazil's Santo Antônio Dam as an example of the need for change

Contents:

APPENDIX A: Hydropower emissions

Emissions are much higher in the humid tropics than in other regions (St Louis et al. 2000; Duchemin et al. 2002; Barros et al. 2011; Demarty and Bastien 2011). Emissions are large in the first years after forming a reservoir (e.g., Galy-Lacaux et al. 1997, 1999; Abril et al. 2005). Old dams continue to emit greenhouse gases at a lower level (e.g., Duchemin et al. 2000; Kemenes et al. 2007, 2011). Emissions have often been underestimated and misrepresented for a variety of reasons (Fearnside and Pueyo 2012). Many estimates omit the major source of CO_2 from decay of trees killed by flooding (see Fearnside 1995; Abril et al. 2013), and omission of methane from water passing through the turbines and spillways is also common.

Since turbines and spillways normally draw water from below the thermocline that divides the water column into layers, the water entering the turbines and spillways has both a high CH_4 concentration and high hydrostatic pressure. When this water is released below the dam, the pressure drops abruptly and the gas is released to the atmosphere. Many estimates of hydroelectric emissions omit turbine and spillway emissions completely, while others consider only the gas flux that can be measured from the water surface some distance downstream of the dam (i.e., after much of the CH_4 has already escaped to the atmosphere). Substantial emissions from turbines have been measured directly at the Balbina Dam in Brazil and the Petit Saut Dam in French Guiana (Abril et al. 2005; Kemenes et al. 2007, 2011). Large emissions have been calculated based on measurements of CH_4 concentrations at other Amazonian dams such as Tucuruí, Samuel and Curuá-Una (Fearnside 2002, 2005a,b).

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APPENDIX B: Sustainable development in the CDM

Hydroelectric projects have very severe social and non-carbon environmental impacts (e.g., Fearnside 1989, 1999, 2001, 2005; Switkes 2008; WCD 2000). Impacts of the Santo Antônio Dam are reviewed in the book entitled *Muddy Waters* (Switkes 2008), in some of the chapters in the review of the EIA by Brazil's Public Ministry (Brazil, MPE-RO 2006) and in other sources on the impacts of the dam (e.g., Vera-Diaz et al. 2007).

Contribution to sustainable development is viewed by many observers as a notable failure of the CDM as a whole; one survey even found that less than 1% of CDM projects actually contributed to sustainable development (Sutter and Parreño 2007), and other assessments show the difficulties facing efforts to assure a contribution to sustainable development (Lecocq and Ambrosi 2007; Olhoff et al. 2004; Tewari 2012). On the other side, strong sustainable-development benefits are pointed out in a study commissioned by the UNFCCC (TERI 2012) and by a UNFCCC "policy dialogue" panel composed of high-level individuals such as the president of Brazil's National Bank for Economic and Social Development (BNDES) (CDM Policy Dialogue 2012; UNFCCC 2011, 2012a,b).

Brazil's internal regulations require that public comments be solicited on proposed CDM projects and that the proposals include a section ("Annex III") that describes sustainable-development implications. A study of social elements in hydroelectric CDM projects in Brazil found that the DNA's review of Annex III submissions and any responses to invitations to comment are relegated to "a relatively toothless ad hoc qualitative assessment" and that there is no "indication that any project has been declined or required to enhance its SD [sustainable development] benefits" (Cole and Roberts 2011, p. 366). Although Brazil's DNA for the CDM has worked much harder than most to insure that CDM projects contribute to sustainable development (Friberg 2009), this obviously does not extend to rejecting proposals with high political priority, such as those that are aligned with the Brazilian government's drive to expand hydropower in Amazonia. In fact, Brazil's DNA has "only questionable authority to reject a proposed CDM project unless it is contrary to existing Brazilian law or regulations with the force of law" (Cole and Liverman 2011, p. 148). In September 2013 the current head of Brazil's DNA told this author that Brazil has no operational definition of sustainable development that would allow him to reject projects on the grounds that they fail to meet the criteria; what exists is a general list of areas such as that a project must create employment, but that even if a project claimed to create only a single job the project could not be rejected. He offered the example of the Madeira River: even if the dams stated in their CDM projects that the giant catfish of the Madeira River would be eliminated, they could not be rejected on the basis of failing to meet sustainable development criteria. Subsidies from sale of carbon credit for dams with heavy environmental and social impacts erode the public image of the Climate Convention, with damaging consequences for present and future efforts to mitigate global climate change.

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APPENDIX C: Emissions in the Santo Antônio Project Design Document

The Project Design Document (PDD) for the Santo Antônio Dam's proposal for carbon credit from the CDM (Santo Antônio Energia S.A. 2011) refers to various Brazilian government documents that support promotion of hydroelectric dams as a means of mitigating greenhouse-gas emissions. Although emissions per kWh from Santo Antônio can be expected to be significantly lower than those in existing Amazonian dams, they will not be zero as claimed by the project. Despite the document's using zero as the emission for the project in its calculation of climate benefits, a table is included (Santo Antônio Energia S.A. 2011, p. 10, Table S4) where the admission is made that the dam would produce methane, although no quantities are mentioned. The same table also states that emissions of carbon dioxide and nitrous oxide (N_2O) are zero, each of these being only a "minor emission source." However, creating a reservoir kills forest trees in the flooded area; some were left projecting out of the water (as in most Amazonian dams) while others were removed from the reservoir area; in both cases the wood will decay in the presence of oxygen, thus producing CO_2. The greatest emissions occur in the first decade. Nitrous oxide is also emitted by tropical reservoirs (Guérin et al. 2008; de Lima et al. 2002). Emissions from construction of the dam and transmission line are not included in the PDD´s calculations.

With the exception of bays and tributaries along the reservoir edges, the water in the Santo Antônio reservoir moves fast enough to prevent stratification. Calculations based on residence time and Froude density both indicate no stratification in the main reservoir (FURNAS et al. 2005, Tomo B, Vol. 7, Anexo II, pp. 3.8-3.9). However, in edge areas where water velocities are much lower than the average for the reservoir as a whole, anoxic water is expected at the bottom of the reservoir, with resulting formation of methane in the sediments (Forsberg and Kemenes 2006). In response to demands from the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA), the proponents performed water-quality simulations for the tributaries in May 2007. The simulations indicated that the water would stratify year-round in two tributaries that have now been converted into branches of the Santo Antônio reservoir (see Appendix D). Some of the methane produced in the stratified areas would be released through diffusion and bubbling, but most of the dissolved methane that does not reach the surface will be prevented from reaching the turbines because the methane would be oxidized when the water from these tributaries mixes with oxygenated water in the main channel. Methane emissions will therefore be lower than in typical Amazonian dams where the main body of the reservoir stratifies. A measurement of high methane flux from the water surface in the two tributaries entering the Santo Antônio reservoir (Hällqvist 2012, p. 25) indicates that the water there is indeed stratified, while a high methane concentration in the air 3 km below the Santo Antônio Dam (Grandin 2012, p. 28) indicates that not all CH_4 is oxidized to CO_2 before reaching the turbines and spillway.

The PDD for the Santo Antônio CDM project calculates reservoir area for the purpose of computing the power density, which is the installed capacity in Watts divided by the area in square meters. The area of the reservoir used is calculated as area at the normal maximum water level of 70.5 m (354.40 km^2), minus 164.00 km^2 described as “the river course," making the increased flooded area 190.40 km² (Santo Antônio Energia S.A. 2011, p. 6).

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APPENDIX D: An estimate of emissions from the Santo Antônio project

Deforestation emissions

CO_2 emissions from biomass decay can be calculated from the dry weight of biomass present, assuming the 50% carbon adopted in the EIA. The estimates in the EIA are only for above-ground biomass, and the optimistic assumption is made here that there is no emission from decay of roots, which would increase the total by slightly over 20%. The EIA includes an estimate of fine litter stocks but is unclear as to whether its biomass estimates include trees less than 10 cm diameter at breast height, non-tree components (lianas, strangler figs, etc.) and dead trees, either standing or fallen. Here it is conservatively assumed these components were included. On the other side, the above-ground biomass estimate given in the EIA for the main forest type -- open ombrophilous (shade-loving) alluvial forest -- appears to be high at 364.67 t/ha dry weight (FURNAS et al. 2005, Tomo B, Vol. 3, p. IV-522). An estimate for this forest type based on 146 one-hectare plots in Brazil’s Radambrasil survey indicates an above-ground biomass of 298.4 ± 60.7 t/ha (Nogueira 2008). The Radambrasil survey was carried out before much of the forest was degraded through logging, so the mean biomass today would be somewhat lower. Table S1 presents an estimate of deforestation emissions.

Table S1: Deforestation emissions

Dam	Biomass dry wt. (t/ha)	Carbon loading (t/ha)	Area (ha)	Carbon stock (t)	Biomass reference	Area reference
Alluvial ombrophilous forest (Fal)						
Trees	364.67	182.3	9,077.0	1,654,730	(a)	(b)
Litter	15.02	7.51	9,077.0	68,168	(c)	(b)
Várzea (floodplain) pioneer formations (Fpv)	18	9	1,371.7	12,345	(d)	(b)
Pasture	1.5	0.75	1,698.7	1,274	(e)	(b)
Riverside human occupation, urban areas & deforestation	5	2.5	107.6	269	(f)	(g)
Deforestation in surrounding area stimulated by the dam			not included			
Dam total			21,332	1,736,786		
CO_2e (h)				6,368,215		
Transmission line						
Forest cleared for transmission line	259	129.5	531.0	68,765	(i)	(j)
CO_2e (h)				252,137		

(a) FURNAS et al. 2005, Tomo B, Vol. 3, p. IV-522.

(b) FURNAS et al. 2005, Tomo B, Vol. 3, p. IV-267.

(c) FURNAS et al. 2005, Tomo B, Vol. 7, Anexo II, p. 4.4.

(d) Schöngart et al. 2010.

(e) Fearnside, 1989, p. 45: average in two pastures in Ouro Preto do Oeste, Rondônia for November, when Santo Antônio's when filling occurred.

(f) FURNAS et al. 2005, Tomo B, Vol. 7, Anexo II, p. 4.12.

(g) Biomass for riverside human occupation, urban areas and deforestation is a guess.

(h) Assumes all carbon is released as CO_2. Converted to CO_2e multiplying by the molecular weight of CO_2 (44) and dividing by the atomic weight of carbon (12) and multiplying by the GWP of CO_2 (1 by definition).

(i) Fearnside et al. 2009 for Rondônia forests.

(j) Bragança 2012.

Reservoir emissions above the dam

Methane emissions from the reservoir surface can be estimated based on existing flux measurements at Santo Antônio. Water in the main channel of the reservoir releases very little methane, but in tributaries the situation is different, and in beds of macrophytes (water weeds) the emission is very high. Measurements of CH_4 concentrations in the air and in the surface water at Santo Antônio provide an indication of substantial methane flux. Normally, the concentration in the water is much higher than the concentration in the air, as CH_4 released into the air is quickly mixed with the vast volume of air that is blown by wind from areas away from the reservoir's influence. The difference in concentration (on a molar basis in the air in the headspace) will result in diffusion from the water to the air. The measurements at Santo Antônio (Grandin 2012; Hällqvist 2012) indicate concentration in the air at least 10 times lower than in the water at all seven sampling stations in the reservoir and its tributaries.

Thermal stratification of the water column is the normal way that anoxic or hypoxic water forms at the bottom, thereby providing the conditions for formation of methane. Warmer water at the surface is separated by a thermocline from colder water at the bottom, thus allowing oxygen to be depleted at the bottom as decomposition removes it from the water to form CO_2. Stratification in the tributaries entering the Santo Antônio reservoir has been documented for parts of the year in all four tributaries monitored by a consulting firm hired by Santo Antônio Energia for this purpose, with data available from September 2011 through January 2013 (Ecology Brasil 2013). The month of February, when the methane flux measurements were made (Grandin 2012; Hällqvist 2012), is not a month with evident stratification. In September, October and November (the low-flow period) all tributaries were stratified, with dissolved oxygen concentrations < 2 mg/L near the bottom, while some tributaries were also stratified in August, December and January (Ecology Brasil 2013). In the main river, the monitoring station (located 8.5 km above the dam) indicated thermal stratification from August to December; dissolved oxygen levels declined at the bottom in these months but never reached the very low levels found in the tributaries: the bottom water in the Rio Madeira had dissolved oxygen in the 5.7-6.5 mg/L range in August, September, October, December and January (Ecology Brasil 2013). A substantial decrease in dissolved oxygen throughout the water column was reported for March and April.

The approximate total emission from the reservoir surface can be calculated as follows. The main channel produces little emission because water velocities are sufficient to avert stratification, at least considering average values by month and river stretch. At low water (5000 m^3/s) flow velocities in different stretches of the reservoir range from 0.11 to 0.27 m/s, at the approximate mean streamflow (18,000 m^3/s) they range from 0.38 to 0.90 m/s, and under flood conditions (48,600 m^3/s) they range from 1.01 to 2.45 m/s (FURNAS and CNO 2007, Anexo 1, pp. 12-16).

The emission from the main channel of the reservoir based on the mean CH_4 flux at four measurement stations in this part of the reservoir is 0.16 mmole/m^2/day (SD=0.33) (Grandin 2012, p. 31). This is equivalent to 2.52×10^{-3} g/m^2/day, and the 236.8 km^2 area to which this applies at the operating water level 70 m above sea level would therefore release 217.8 t/year of methane. The 70-m operating level is specified in the viability study and environmental impact study (EIA) for the dam; the level used in the Project Design Document (PDD) for the carbon project was 70.5 m. With the recently approved increase to 71.3 m above sea level the area would be 272.2 km^2 based on information in the EIA (FURNAS et al. 2005, Tomo A, Vol. 1, p. VII-54; FURNAS and CNO 2007, pp. 125-126), and the emission would be 250.4 t/year.

The area figures given above do not adjust for the loss of reservoir area when the Jirau Dam was moved 9 km downstream, but the difference in emission would be quite small relative to other sources. Note that the Project Design Document (PDD) for the Santo Antônio carbon project, which was submitted after the location of the Jirau Dam had been moved, gives 354.4 km^2 as the reservoir area at the 70.5-m water level (Santo Antônio Energia S.A. 2011, p. 35), or 22.7% higher than the area at this water level given in the EIA. The reservoir was operating at 70.5 m as of April 2014, and the 17 turbines that had been installed by then did not required the additional head from the 71.3 m level.

The tributaries are a much greater source of emission than the body of the reservoir. Unlike the main channel of the river, calculations by the dam proponents indicated that the tributaries would be stratified during all or part of the year (FURNAS and CNO 2007, pp. 150-151). The areas of the three tributaries are: Igarapé Mucuim (Teotonio) 4.55 km^2 at the 70 m water level, 4.92 km^2 at 70.5 m and 5.43 km^2 at 71.3 m; Igarapé Jatuarana 11.11 km^2 at 70 m, 11.53 km^2 at 70.5 m and 12.28 km^2 at 71.3 m; Jaci-Paraná River 18.51 km^2 at 70 m, 20.11 km^2 at 70.5 m and 28.16 km^2 at 71.3 m (FURNAS and CNO 2007, pp. 125-126). These total 34.17 km^2 at 70 m, 38.56 km^2 at 70.5 m and 45.87 km^2 at 71.3 m. The percentage of this area that is covered with macophytes will be a key factor in determining the emission.

Rooted macrophytes (water weeds) represent an important emissions source for methane, as the xylem in their stems provides a direct conduit for gas transfer from the anoxic sediments to the atmosphere. Tropical reservoirs typically experience explosions of macrophyte populations (both rooted and not) in the first years after impoundment, as at Brokopondo in Surinam (Leentvaar 1966), Balbina in Brazil's state of Amazonas (Walker et al. 1999) and Tucuruí in the state of Pará (de Lima et al. 2000). At Tucuruí, for example, a sequence of satellite images indicates that 39% of the reservoir was covered by macrophytes two years after impoundment, after which the cover declined and stabilized at 11% of the reservoir in the tenth year (de Lima et al. 2000). At Santo Antônio an overflight of the reservoir shortly after filling revealed very extensive macrophyte cover (Francisco Pereira, personal communication 2012). It is in the tributaries and in shallow bays along the reservoir edges that macrophytes persist most after the initial flush of macrophyte cover has passed, and it also in these locations where macrophytes are mostly rooted. Measurements of methane fluxes from a macrophyte patch in a tributary to the Santo Antônio reservoir (the Jaci-Paraná River) in February 2012 indicated an emission rate of 127.12 mmol CH_4/m^2/day, considering the concentration in the flux chamber 20 minutes after placement (Note: CH_4 concentrations in flux chambers increase over the course of a standard 30-minute measurement sequence, but, in the case of this measurement, the concentration in the chamber declined to a level corresponding to 36.44 mmol CH_4/m^2/day over the next 10-

minute interval due to a probable break in the seal between the water and the chamber: Grandin 2012, p. 28; Hällqvist 2012, p. 39). The comparable measurement for an adjacent sample without macrophytes was 7.56 mmole/m^2/day. The difference of 119.56 mmole/m^2/day, representing the emission from the macrophytes, is 16 times higher than the emission from the water surface.

If one makes a conservative guess that only 20% of the tributary area is covered with macropytes (i.e., 2.5% of the reservoir as a whole at the 70-m, 2.4% at the 70.5-m level, or 2.9% at the 71.3-m level), then the measured emission of 127.12 mmol CH_4/m^2/day in macrophytes described above implies an emission of 5073.4 t/year at the 70-m level, 5725.2 t/year at 70.5 m and 6810.5 t/year at 71.3 m. The remaining 80% of the tributary surface emitting at 21.1 mmole/m^2/day (SD=16.6, n=3 stations) (Grandin 2012, p. 31) implies an emission of 3367.9 t/year at the 70-m level, 3800.6 at the 70.5-m level and 4521.0 t/year at the 71.3-m level.

Emissions below the dam

In the case of a sampling station located approximately 3 km below the dam (Hällqvist 2012, p. 18), the concentration in the air was 8.4 ppmv, or 5.5 times higher than the concentration found in the water (Grandin 2012, p. 28). Concentrations were also measured at two sampling stations much farther downstream, with mixed results. At a station approximately 29 km below the dam the concentration in the air was only 2 ppmv, while that in the water was 17.5 times higher, or similar to the concentrations in Santo Antônio's tributaries. The other station, located approximately 100 km below the dam, had concentrations similar to those at the station located 3 km below the dam, with a concentration in the air of 13.3 ppmv, or 8.6 times higher than the concentration in the water.

The emission immediately below the dam is of a different type from the emission from the water surface in tributaries within the reservoir. In the case of the tributaries, emission is continuous, with the surface water having high concentrations of CH_4 that is continually replenished by anaerobic decomposition in the sediments below, and the air at 30-cm height above the water has a much lower CH_4 concentration than the water. At the sampling station 3 km below the dam, however, the relationship is reversed, with a greatly enhanced CH_4 concentration in the air, but little in the water. This indicates that, rather than a continuous flux of CH_4 through the water column and diffusion at the surface, the gas has been released in a single burst (presumably mainly of bubbles) as the water emerges from the turbines and spillway. The gas in the air remains over the river for a considerable distance downstream, but the rate of flux at the surface as the water continues to flow downstream would be small – much less than would be needed to explain the elevated concentration of CH_4 at 30 cm height.

Even if the turbulent water in the stretch of river below the dam did not prevent direct flux measurements with chambers, the measurements would tell us little about the amount of CH_4 that had been emitted in the initial burst. Likewise, if data were available on the vertical component of air movement, the total emission could not be calculated from the air concentration because the emission is not a continuous flux. Nevertheless, a very rough idea can be had of a minimum value for this release. It is known from studies of CO_2 concentration profiles in the air column over Amazonian cattle pastures that during the night, if the air is not still, the gas concentration is approximately constant up to a boundary layer height, which, based on two estimation methods, averages 51 m above the surface (Acevedo et al. 2004, p. 893). This refers to a gas (CO_2) coming from a continuous source, namely respiration of the vegetation at night, making it different from a one-time pulse of emission as in the case of CH_4 degassing from the turbines and spillway. The concentration at 30-cm height cannot be extrapolated up to a height of 51 m. However, one can make a conservative assumption, such as that, on average, the air column contains this concentration up to a height of 5 m (i.e., 10% of the approximate height to which the air mass can be assumed to rise at night).

The Madeira River just below the dam has a width of 2.2 km, narrowing to 1.4 km in front of Porto Velho and to 0.8 km below the city (measured from Google Earth). If one assumes that the air mass containing the methane remains over the river course for 6 km (i.e., twice the distance to the first sampling station below the dam, the methane load above the first sampling station therefore representing the half-way point in a presumed linear decline beginning from the dam), and considering the river width of 1.4 km (corresponding to that at the measurement station 3 km below the dam) as most relevant to dissipation of the initial emission from water passing through the dam, the volume of the air mass containing the methane is 4.20×10^7 m^3. Considering the average air temperature of 33 °C at the reservoir measurement sites (Grandin 2012, p. 31), the altitude of the river surface of 55.3 m above sea level (FURNAS et al. 2005, Tomo A, Vol. 1, p. VII-50), the air density at this altitude and temperature is 0.68% less than that at standard temperature and pressure, which is equivalent to 0°C at sea level (Engineering Toolbox 2014).

The average concentration in the air at the four sites on the main reservoir of 1.4 ppmv CH_4 (Hällqvist 2012, p. 27) can be taken as the background concentration for the standpoint of calculating enrichment. The concentration measurements in the air were made at the level of the top of the floating chambers, or approximately 30 cm above the water (Hällqvist 2012, pp. 12-13).

At the temperature and altitude at Porto Velho, one mole of gas occupies 22.55 liters, and the air mass above the river contains 1.86×10^9 moles of air. The methane enrichment of 8.4 – 1.4 = 7.0 ppmv corresponds to 1.30×10^4 moles of methane in the air mass, or 208.6 kg of methane gas. In the month of February, when the methane measurements were made, the prevailing winds at the site are from the north (Cortez 2004, p. 17), meaning that the wind has an angle of attack of 35° with respect to the axis of the river, which (ignoring irregularities) flows in a roughly northeasterly direction in this stretch at an angle of 35° (Google Earth). The average wind speed at the time of the measurement at the sampling station 3 km below the dam was 2.3 m/s (Hällqvist 2012, p. 35). The average wind speed in Porto Velho over the year is 1.4 m/s (Cortez 2004, p. 16). The measured wind speed and the assumed direction imply that the vector representing movement across the river had a velocity of 1.3 m/s. The air over the river was therefore being renewed every 18 minutes, and the total amount of CH_4 emitted corresponded to 27 t/day or 1.67×10^4 t/year.

The total estimated emission from fluxes above and below the dam is 1.48 × 10^4 t/year at the 70-m water level, 1.59 × 10^4 t/year at the 70.5-m level and 1.77 × 10^4 t/year at the 71.3-m level. Of this 41.3% represents downstream emission at the 70-m level, the corresponding percentages being 38.3% for 70.5 m and 34.5% for 71.3 m. The downstream emission is probably primarily from immediate release as the water passes through the dam and would not continue at a significant level from the water surface beyond the measurement point 3 km below the dam.

Some rough reality checks are possible based on the amount of methane that would be transported through the dam at different possible concentrations. Given the 1931-2005 mean streamflow of 18,806 m^3/s, the calculated annual downstream CH_4 emission of 175,024 t represents 15.4% of the 1.14 × 10^6 t/year of methane transported through the dam if the water contained the high mean concentration found in the surface water in the tributaries, but it represents an impossible 410% of the methane passing through the dam (42,730 t/year) if the water contained the concentration measured in surface water in the main river at the closest measurement station above the dam. However, methane concentrations measured at the surface do not represent the average concentration in the water column, especially if the water is stratified, since methane concentrations at the bottom of the reservoir under these conditions are much higher than at the surface. The surface water concentration below the dam being essentially equal to that above the dam means that the methane enrichment of the air is not explained by release of the transported methane as calculated from the surface concentration, and therefore must be from release of methane at higher concentration near the bottom of the river. At the time of the measurement almost all of the river’s flow was passing through the spillway, which draws water from deep in the water column and which produces strong turbulence below the dam. A release of this magnitude therefore does not appear unreasonable, but uncertainty is high.

Another check is the percentage of the total methane emission that is estimated to occur downstream, in this case 34.5% for the 70.5-m water level. This percentage is well below those at other dams in tropical South America: Balbina at age 18 years emitted 52.7% of its CH_4 downstream (Kemenes et al. 2007), Petit Saut at age 9 years emitted 78.6% downstream (Abril et al. 2005) and Tucuruí at age 6 years emitted 88.2% downstream (Fearnside 2002). These other dams have significant differences from Santo Antônio, including substantially larger reservoir areas that would lead to a smaller expected importance of downstream emissions as a percentage of the total. The larger streamflow of the Madeira River as compared to the rivers at the other South American dams would also make the expected percentage of downstream emissions greater at Santo Antônio. The lower downstream percentage calculated for Santo Antônio is therefore a feature suggesting that the estimate of downstream emissions is conservative.

I emphasize that the above estimate for Santo Antônio is a very rough calculation, but it gives an idea of the magnitude involved with the best information available. The above estimate contains a variety of conservative assumptions. Perhaps the greatest is that the methane concentration in the air from a measurement made approximately 3 km below the dam represents the value to be applied to the air mass above the river. Because the bulk of emission typically occurs very quickly as the water passes through the dam (see Fearnside and Pueyo 2012), the value used here is probably an underestimate because much of the methane from the initial burst of emission would have already been blown laterally away from the river before reaching the point of measurement.

Dam and transmission line construction emissions

Dam and transmission line emissions are shown in Table S2. The dam construction emissions estimate is conservative, since lack of information results in not including a number of emission sources such as diesel fuel and electricity use. In the transmission line estimate, emissions from production of the 63,000 t of aluminum used in the cables is undoubtedly underestimated, since the emissions from the highly energy-intensive process of aluminum production are calculated from estimates from the Brazilian Association of Aluminum (ABAL 2011) that consider hydropower to be “green” emissions-free energy.

Table S2: Santo Antônio dam and transmission line construction emissions

Category	Item	No. of Items	Amount per item	Total amount	Units	Emission per unit (t CO_2e)	Total emission (t CO_2e)	Amount Reference	Emission Reference
Steel									
	Reinforcing rods			167,837	t			(a)	
	Turbines	44	899.36	39,572	t			(a)	
	Generators	44	234.53	10,319	t			(a)	
	Spillway gates	21	234.53	4,925	t			(b)	
	Other steel			2,500	t			(b)	
	Total steel			225,153	t	2.200	495,336		(c)
Concrete									
	Conventional concrete			3,311,150	t			(a)	
	Roller compressed concrete			408,000	t			(a)	
	Total concrete			3,719,150	t				
	Sand and gravel in concrete			2,769,688	t	0.009	25,758	(d)	(e)
Cement				949,462	t	1.004	953,545	(a)	(e)
Excavation and fill									
	Ordinary excavation			74,364,110	m^3			(a)	(d, f)
	Rock above water			21,554,760	m^3			(a)	(d, f)
	Rock below water			400,000	m^3			(a)	(d, f)
	Earth fill			6,164,780	m^3			(a)	(d, f)
	Rock fill			5,852,870	m^3			(a)	(d, f)
	Rip-rap			1,534,566	m^3			(a)	(d, f)
	Total excavation and fill			109,871,086	m^3	0.0006	68,197		(f)
Dam subtotal							1,542,836		

Transmission line							
	Steel	52,000	t	2.200	114,400	(g)	(c)
	Aluminum	63,000	t	4.250	267,750	(g)	(h)
	Transmission line total				382,150		
	Fraction of transmission line attributed to Santo Antônio	0.5					
Transmission line subtotal attributed to Santo Antônio					191,075		
Total attributed to Santo Antônio					1,733,911		

(a) FURNAS and CNO 2008.
(b) Based on Belo Monte (Fearnside 2009).
(c) Van Vate 1995.
(d) Concrete minus cement.
(e) Marheineke nd [1996].
(f) Emissions for "earth haulings" applied to all excavation and fill operations.
(g) Moreira 2013.
(h) ABAL 2011, p. 38.

Comparison of Santo Antônio with baseline emissions

Estimated emissions of Santo Antônio (including downstream emissions) are compared to baseline emissions in Table S3. Table S4 makes the same comparison omitting the very uncertain downstream emissions.

Table S3: Estimated emissions from Santo Antônio (Reservoir at 70.5 m + downstream) compared to baseline emissions

		Baseline emissions (t CO_2e) (a)		Power to be generated (MWh)	Estimated emission from Sto. Antonio			
					CH_4 (t/yr)	GWP=25 (t CO_2e)	GWP=34 (t CO_2e)	GWP=86 (t CO_2e)
Dam construction CO_2 emissions (Table S2)						1,542,836	1,542,836	1,542,836
Dam deforestation CO_2 emissions (Table S2)						6,368,215	6,368,215	6,368,215
Transmission line construction CO_2 emissions attributed to Santo Antônio (Table S2)						191,075	191,075	191,075
Transmission line deforestation CO_2 emissions (Table S1)						252,137	252,137	252,137
Gas-fired power plant construction CO_2 emissions		2157.8	(b)					
0	2012	518,205		1,893,741	15,911	397,782	540,984	1,368,371
1	2013	2,720,189		9,940,726	15,911	397,782	540,984	1,368,371
2	2014	4,953,586		18,102,507	15,911	397,782	540,984	1,368,371
3	2015	5,830,126		21,305,757	15,911	397,782	540,984	1,368,371
4	2016	5,846,099		21,364,129	15,911	397,782	540,984	1,368,371
5	2017	5,830,126		21,305,757	15,911	397,782	540,984	1,368,371
6	2018	5,830,126		21,305,757	15,911	397,782	540,984	1,368,371
7	2019	5,830,126		21,305,757	15,911	397,782	540,984	1,368,371
8	2020	5,846,099		21,364,129	15,911	397,782	540,984	1,368,371
9	2021	5,830,126		21,305,757	15,911	397,782	540,984	1,368,371
10	2022	2,429,219		8,877,398	15,911	397,782	540,984	1,368,371
Total		51,466,185		188,079,300	175,024	12,729,868	14,305,086	23,406,345
Transmission loss to São Paulo(c)		10,293,237	(d)	37,615,860				
Power delivered to São Paulo		41,172,948		150,463,440				
Emission per MWh delivered to São Paulo (t CO_2e/MWh)		0.27				0.08	0.10	0.16

(a) Baseline emissions (Santo Antônio Energia S.A. 2011, p. 35) are based on the Combined Margin Emissions Factor of 0.31, which is 50% from the Grid Operating Margin Emissions Factor (0.4796) and 50% from the Grid build margin emissions factor (0.1404) (Santo Antônio Energia S.A. 2011, p. 34).

(b) Based on the 230-t Alstom GT24 gas turbine, considered state-of-the-art; this 700-MW capacity turbine operates with a 60% power factor

(Wheeler 2012). This would supply a total of 62,362,000 MWh over a period of 10 years, and 4.1 of these turbines would supply the electricity Santo Antônio will deliver to São Paulo.

(c) Assumes 20% transmission loss, the mean for Brazilian losses (Rey 2012). This is conservative for a line of this length.

(d) Although gas-fired plants are built where electricity is used, thereby avoiding transmission loss, the amount of electricity used for calculating baseline emissions in the PDD is based on power delivered to the grid 5 km from the Santo Antônio Dam.

Table S4: Estimated emissions from Santo Antônio (Reservoir only, 70.5 m water level) compared to baseline emissions

		Baseline emissions (t CO_2e) (a)		Power to be generated (MWh)	Estimated emission from Sto. Antonio			
					CH_4 (t/yr)	GWP=25 (t CO_2e)	GWP=34 (t CO_2e)	GWP=86 (t CO_2e)
Dam construction CO_2 emissions (Table S2)						1,542,836	1,542,836	1,542,836
Dam deforestation CO_2 emissions (Table S1)						6,368,215	6,368,215	6,368,215
Transmission line construction CO_2 emissions attributed to Santo Antônio (Table S2)						191,075	191,075	191,075
Transmission line deforestation CO_2 emissions (Table S1)						252,137	252,137	252,137
Gas-fired plant construction CO_2 emissions		2157.8	(b)					
0	2012	518,205		1,893,741	9,816	245,409	333,756	844,207
1	2013	2,720,189		9,940,726	9,816	245,409	333,756	844,207
2	2014	4,953,586		18,102,507	9,816	245,409	333,756	844,207
3	2015	5,830,126		21,305,757	9,816	245,409	333,756	844,207
4	2016	5,846,099		21,364,129	9,816	245,409	333,756	844,207
5	2017	5,830,126		21,305,757	9,816	245,409	333,756	844,207
6	2018	5,830,126		21,305,757	9,816	245,409	333,756	844,207
7	2019	5,830,126		21,305,757	9,816	245,409	333,756	844,207
8	2020	5,846,099		21,364,129	9,816	245,409	333,756	844,207
9	2021	5,830,126		21,305,757	9,816	245,409	333,756	844,207
10	2022	2,429,219		8,877,398	9,816	245,409	333,756	844,207
Total		51,466,185		188,079,300	107,980	11,053,763	12,025,583	17,640,543
Transmission loss to São Paulo(c)		10,293,237	(d)	37,615,860				
Power delivered to São Paulo		41,172,948		150,463,440				
Emission per MWh delivered to São Paulo (t CO_2e/MWh)			0.27			0.07	0.08	0.12

(a) Baseline emissions (Santo Antônio Energia S.A. 2011, p. 35) are based on the Combined Margin Emissions Factor of 0.31, which is 50% from the Grid Operating Margin Emissions Factor (0.4796) and 50% from the Grid build margin emissions factor (0.1404) (Santo Antônio Energia S.A. 20121p. 34).

(b) Based on the 230-t Alstom GT24 gas turbine, considered state-of-the-art; this 700-MW capacity turbine operates with a 60% power factor (Wheeler 2012). This would supply a total of 62,362,000 MWh over a period of 10 years, and 4.1 of these turbines would supply the electricity Santo Antônio will deliver to São Paulo.

(c) Assumes 20% transmission loss, the mean for Brazilian losses (Rey 2012). This is conservative for a line of this length.

(d) Although gas-fired plants are built where electricity is used, thereby avoiding transmission loss, the amount of electricity used for calculating baseline emissions in the PDD is based on power delivered to the grid 5 km from the Santo Antônio Dam.

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APPENDIX E: Explanation of PDD additionality calculation

Half of the Weighted Average Cost of Capital (WACC) value is represented by the cost of debt (calculated to be 3.39%), and the other half is the cost of capital, which is calculated at 17.31% by adjusting a Risk-free rate of 4.88% for an Equity risk premium of 6.57%, which is increased by multiplying by a Sectorial Risk (β) value of 1.34), a country risk premium of 6.06%, and expected US inflation of 2.39% (Santo Antônio Energia, S.A. 2011, p. 14).

The PDD (Santo Antônio Energia, S.A. 2011, pp. 13-14) calculates the WACC of the hydropower sector for 2007 using Equation 1.

$$WACC = (Wd \times Kd) + (We \times Ke) \qquad \text{(eq. 1)}$$

Where:

We = weight of equity typically observed” in the hydropower sector: 50%

Wd = weight of debt “typically observed” in the hydropower sector: 50%

Kd is the cost of debt in the hydropower market; this includes adjustments for the tax benefits of contracting debts. Kd is calculated from Equation 2.

$$Kd = [1 + (a+b+c) \times (1-t)]/ [(1+d) -1] \qquad \text{(eq. 2)}$$

Where:
(a) = Financial cost: 9.28%
(b) = BNDES fee: 0.90%
(c) = Spread: 2.00%
(a+b+c) = Pre-Cost of Debt: 12.18%
(t) = Marginal tax rate: 34.00%
(d) = Inflation forecast: 4.50%

From Equation 2, the after-tax Cost of Debt (Kd) is 3.39% per year.

Ke (cost of equity) represents the rate of return for equity investments. Based on the PDD (Santo Antônio Energia 2011, p. 14) as clarified from spreadsheets, it is estimated with Equation 3:

$$Ke = ((Rf + (\beta \times Rm) + Rc) \times (I / d) \qquad \text{(eq. 3)}$$

Where:
(Rf) = Risk-free rate: 4.88%
(Rm) = Equity risk premium = 6.57%
(Rc) = Estimated country risk premium = 6.06%
(β) = Sector Risk = 1.34
(I) = US expected inflation: 2.39%

(d) = Brazilian Inflation forecast: 4.50%
From Equation 3 the Cost of Equity with Brazilian Country Risk is:

$Ke = (0.0488 + (1.34 \times 0.0657) + 0.0606) \times (0.0239 / 0.0450) = 0.1731$

or 17.31% per year.

From Equation 1 the Weighted Average Cost of Capital (WACC) is:

$WACC = (50\% \times 3.39\%) + (50\% \times 17.31\%) = 10.35\%$

Reference

Santo Antônio Energia S.A. (2011) Santo Antonio Hydropower Project. PDD version: 01.1 (27/10/2011) Clean Development Mechanism Project Design Document Form (CDM-PDD) Version 03. Santo Antônio Energia S.A., Porto Velho, Rondônia, Brazil. 53 pp. url:http://cdm.unfccc.int/filestorage/E/9/C/E9CIR7WM1SUB4X5QPVHA6KG0ZJLTFO/Santo%20Antonio_PDD_20022012.pdf?t=NHl8bjNxeWdxfDD80ZqBJV6OAqLeVCB6tBCq

17 December 2014

Supplementary Online Material

Tropical Hydropower in the Clean Development Mechanism: Brazil's Santo Antônio Dam as an example of the need for change

Contents:

APPENDIX A: Hydropower emissions

Emissions are much higher in the humid tropics than in other regions (St Louis et al. 2000; Duchemin et al. 2002; Barros et al. 2011; Demarty and Bastien 2011). Emissions are large in the first years after forming a reservoir (e.g., Galy-Lacaux et al. 1997, 1999; Abril et al. 2005). Old dams continue to emit greenhouse gases at a lower level (e.g., Duchemin et al. 2000; Kemenes et al. 2007, 2011). Emissions have often been underestimated and misrepresented for a variety of reasons (Fearnside and Pueyo 2012). Many estimates omit the major source of CO_2 from decay of trees killed by flooding (see Fearnside 1995; Abril et al. 2013), and omission of methane from water passing through the turbines and spillways is also common.

Since turbines and spillways normally draw water from below the thermocline that divides the water column into layers, the water entering the turbines and spillways has both a high CH_4 concentration and high hydrostatic pressure. When this water is released below the dam, the pressure drops abruptly and the gas is released to the atmosphere. Many estimates of hydroelectric emissions omit turbine and spillway emissions completely, while others consider only the gas flux that can be measured from the water surface some distance downstream of the dam (i.e., after much of the CH_4 has already escaped to the atmosphere). Substantial emissions from turbines have been measured directly at the Balbina Dam in Brazil and the Petit Saut Dam in French Guiana (Abril et al. 2005; Kemenes et al. 2007, 2011). Large emissions have been calculated based on measurements of CH_4 concentrations at other Amazonian dams such as Tucuruí, Samuel and Curuá-Una (Fearnside 2002, 2005a,b).

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APPENDIX B: Sustainable development in the CDM

Hydroelectric projects have very severe social and non-carbon environmental impacts (e.g., Fearnside 1989, 1999, 2001, 2005; Switkes 2008; WCD 2000). Impacts of the Santo Antônio Dam are reviewed in the book entitled *Muddy Waters* (Switkes 2008), in some of the chapters in the review of the EIA by Brazil's Public Ministry (Brazil, MPE-RO 2006) and in other sources on the impacts of the dam (e.g., Vera-Diaz et al. 2007).

Contribution to sustainable development is viewed by many observers as a notable failure of the CDM as a whole; one survey even found that less than 1% of CDM projects actually contributed to sustainable development (Sutter and Parreño 2007), and other assessments show the difficulties facing efforts to assure a contribution to sustainable development (Lecocq and Ambrosi 2007; Olhoff et al. 2004; Tewari 2012). On the other side, strong sustainable-development benefits are pointed out in a study commissioned by the UNFCCC (TERI 2012) and by a UNFCCC "policy dialogue" panel composed of high-level individuals such as the president of Brazil's National Bank for Economic and Social Development (BNDES) (CDM Policy Dialogue 2012; UNFCCC 2011, 2012a,b).

Brazil's internal regulations require that public comments be solicited on proposed CDM projects and that the proposals include a section ("Annex III") that describes sustainable-development implications. A study of social elements in hydroelectric CDM projects in Brazil found that the DNA's review of Annex III submissions and any responses to invitations to comment are relegated to "a relatively toothless ad hoc qualitative assessment" and that there is no "indication that any project has been declined or required to enhance its SD [sustainable development] benefits" (Cole and Roberts 2011, p. 366). Although Brazil's DNA for the CDM has worked much harder than most to insure that CDM projects contribute to sustainable development (Friberg 2009), this obviously does not extend to rejecting proposals with high political priority, such as those that are aligned with the Brazilian government's drive to expand hydropower in Amazonia. In fact, Brazil's DNA has "only questionable authority to reject a proposed CDM project unless it is contrary to existing Brazilian law or regulations with the force of law" (Cole and Liverman 2011, p. 148). In September 2013 the current head of Brazil's DNA told this author that Brazil has no operational definition of sustainable development that would allow him to reject projects on the grounds that they fail to meet the criteria; what exists is a general list of areas such as that a project must create employment, but that even if a project claimed to create only a single job the project could not be rejected. He offered the example of the Madeira River: even if the dams stated in their CDM projects that the giant catfish of the Madeira River would be eliminated, they could not be rejected on the basis of failing to meet sustainable development criteria. Subsidies from sale of carbon credit for dams with heavy environmental and social impacts erode the public image of the Climate Convention, with damaging consequences for present and future efforts to mitigate global climate change.

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APPENDIX C: Emissions in the Santo Antônio Project Design Document

The Project Design Document (PDD) for the Santo Antônio Dam's proposal for carbon credit from the CDM (Santo Antônio Energia S.A. 2011) refers to various Brazilian government documents that support promotion of hydroelectric dams as a means of mitigating greenhouse-gas emissions. Although emissions per kWh from Santo Antônio can be expected to be significantly lower than those in existing Amazonian dams, they will not be zero as claimed by the project. Despite the document's using zero as the emission for the project in its calculation of climate benefits, a table is included (Santo Antônio Energia S.A. 2011, p. 10, Table S4) where the admission is made that the dam would produce methane, although no quantities are mentioned. The same table also states that emissions of carbon dioxide and nitrous oxide (N_2O) are zero, each of these being only a "minor emission source." However, creating a reservoir kills forest trees in the flooded area; some were left projecting out of the water (as in most Amazonian dams) while others were removed from the reservoir area; in both cases the wood will decay in the presence of oxygen, thus producing CO_2. The greatest emissions occur in the first decade. Nitrous oxide is also emitted by tropical reservoirs (Guérin et al. 2008; de Lima et al. 2002). Emissions from construction of the dam and transmission line are not included in the PDD´s calculations.

With the exception of bays and tributaries along the reservoir edges, the water in the Santo Antônio reservoir moves fast enough to prevent stratification. Calculations based on residence time and Froude density both indicate no stratification in the main reservoir (FURNAS et al. 2005, Tomo B, Vol. 7, Anexo II, pp. 3.8-3.9). However, in edge areas where water velocities are much lower than the average for the reservoir as a whole, anoxic water is expected at the bottom of the reservoir, with resulting formation of methane in the sediments (Forsberg and Kemenes 2006). In response to demands from the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA), the proponents performed water-quality simulations for the tributaries in May 2007. The simulations indicated that the water would stratify year-round in two tributaries that have now been converted into branches of the Santo Antônio reservoir (see Appendix D). Some of the methane produced in the stratified areas would be released through diffusion and bubbling, but most of the dissolved methane that does not reach the surface will be prevented from reaching the turbines because the methane would be oxidized when the water from these tributaries mixes with oxygenated water in the main channel. Methane emissions will therefore be lower than in typical Amazonian dams where the main body of the reservoir stratifies. A measurement of high methane flux from the water surface in the two tributaries entering the Santo Antônio reservoir (Hällqvist 2012, p. 25) indicates that the water there is indeed stratified, while a high methane concentration in the air 3 km below the Santo Antônio Dam (Grandin 2012, p. 28) indicates that not all CH_4 is oxidized to CO_2 before reaching the turbines and spillway.

The PDD for the Santo Antônio CDM project calculates reservoir area for the purpose of computing the power density, which is the installed capacity in Watts divided by the area in square meters. The area of the reservoir used is calculated as area at the normal maximum water level of 70.5 m (354.40 km^2), minus 164.00 km^2 described as “the river course," making the increased flooded area 190.40 km² (Santo Antônio Energia S.A. 2011, p. 6).

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APPENDIX D: An estimate of emissions from the Santo Antônio project

Deforestation emissions

CO_2 emissions from biomass decay can be calculated from the dry weight of biomass present, assuming the 50% carbon adopted in the EIA. The estimates in the EIA are only for above-ground biomass, and the optimistic assumption is made here that there is no emission from decay of roots, which would increase the total by slightly over 20%. The EIA includes an estimate of fine litter stocks but is unclear as to whether its biomass estimates include trees less than 10 cm diameter at breast height, non-tree components (lianas, strangler figs, etc.) and dead trees, either standing or fallen. Here it is conservatively assumed these components were included. On the other side, the above-ground biomass estimate given in the EIA for the main forest type -- open ombrophilous (shade-loving) alluvial forest -- appears to be high at 364.67 t/ha dry weight (FURNAS et al. 2005, Tomo B, Vol. 3, p. IV-522). An estimate for this forest type based on 146 one-hectare plots in Brazil’s Radambrasil survey indicates an above-ground biomass of 298.4 ± 60.7 t/ha (Nogueira 2008). The Radambrasil survey was carried out before much of the forest was degraded through logging, so the mean biomass today would be somewhat lower. Table S1 presents an estimate of deforestation emissions.

Table S1: Deforestation emissions

Dam	Biomass dry wt. (t/ha)	Carbon loading (t/ha)	Area (ha)	Carbon stock (t)	Biomass reference	Area reference
Alluvial ombrophilous forest (Fal)						
Trees	364.67	182.3	9,077.0	1,654,730	(a)	(b)
Litter	15.02	7.51	9,077.0	68,168	(c)	(b)
Várzea (floodplain) pioneer formations (Fpv)	18	9	1,371.7	12,345	(d)	(b)
Pasture	1.5	0.75	1,698.7	1,274	(e)	(b)
Riverside human occupation, urban areas & deforestation	5	2.5	107.6	269	(f)	(g)
Deforestation in surrounding area stimulated by the dam			not included			
Dam total			21,332	1,736,786		
CO_2e (h)				6,368,215		
Transmission line						
Forest cleared for transmission line	259	129.5	531.0	68,765	(i)	(j)
CO_2e (h)				252,137		

(a) FURNAS et al. 2005, Tomo B, Vol. 3, p. IV-522.
(b) FURNAS et al. 2005, Tomo B, Vol. 3, p. IV-267.
(c) FURNAS et al. 2005, Tomo B, Vol. 7, Anexo II, p. 4.4.
(d) Schöngart et al. 2010.
(e) Fearnside, 1989, p. 45: average in two pastures in Ouro Preto do Oeste, Rondônia for November, when Santo Antônio's when filling occurred.
(f) FURNAS et al. 2005, Tomo B, Vol. 7, Anexo II, p. 4.12.
(g) Biomass for riverside human occupation, urban areas and deforestation is a guess.

(h) Assumes all carbon is released as CO_2. Converted to CO_2e multiplying by the molecular weight of CO_2 (44) and dividing by the atomic weight of carbon (12) and multiplying by the GWP of CO_2 (1 by definition).

(i) Fearnside et al. 2009 for Rondônia forests.

(j) Bragança 2012.

Reservoir emissions above the dam

Methane emissions from the reservoir surface can be estimated based on existing flux measurements at Santo Antônio. Water in the main channel of the reservoir releases very little methane, but in tributaries the situation is different, and in beds of macrophytes (water weeds) the emission is very high. Measurements of CH_4 concentrations in the air and in the surface water at Santo Antônio provide an indication of substantial methane flux. Normally, the concentration in the water is much higher than the concentration in the air, as CH_4 released into the air is quickly mixed with the vast volume of air that is blown by wind from areas away from the reservoir's influence. The difference in concentration (on a molar basis in the air in the headspace) will result in diffusion from the water to the air. The measurements at Santo Antônio (Grandin 2012; Hällqvist 2012) indicate concentration in the air at least 10 times lower than in the water at all seven sampling stations in the reservoir and its tributaries.

Thermal stratification of the water column is the normal way that anoxic or hypoxic water forms at the bottom, thereby providing the conditions for formation of methane. Warmer water at the surface is separated by a thermocline from colder water at the bottom, thus allowing oxygen to be depleted at the bottom as decomposition removes it from the water to form CO_2. Stratification in the tributaries entering the Santo Antônio reservoir has been documented for parts of the year in all four tributaries monitored by a consulting firm hired by Santo Antônio Energia for this purpose, with data available from September 2011 through January 2013 (Ecology Brasil 2013). The month of February, when the methane flux measurements were made (Grandin 2012; Hällqvist 2012), is not a month with evident stratification. In September, October and November (the low-flow period) all tributaries were stratified, with dissolved oxygen concentrations < 2 mg/L near the bottom, while some tributaries were also stratified in August, December and January (Ecology Brasil 2013). In the main river, the monitoring station (located 8.5 km above the dam) indicated thermal stratification from August to December; dissolved oxygen levels declined at the bottom in these months but never reached the very low levels found in the tributaries: the bottom water in the Rio Madeira had dissolved oxygen in the 5.7-6.5 mg/L range in August, September, October, December and January (Ecology Brasil 2013). A substantial decrease in dissolved oxygen throughout the water column was reported for March and April.

The approximate total emission from the reservoir surface can be calculated as follows. The main channel produces little emission because water velocities are sufficient to avert stratification, at least considering average values by month and river stretch. At low water (5000 m^3/s) flow velocities in different stretches of the reservoir range from 0.11 to 0.27 m/s, at the approximate mean streamflow (18,000 m^3/s) they range from 0.38 to 0.90 m/s, and under flood conditions (48,600 m^3/s) they range from 1.01 to 2.45 m/s (FURNAS and CNO 2007, Anexo 1, pp. 12-16).

The emission from the main channel of the reservoir based on the mean CH_4 flux at four measurement stations in this part of the reservoir is 0.16 mmole/m^2/day (SD=0.33) (Grandin 2012, p. 31). This is equivalent to 2.52×10^{-3} g/m^2/day, and the 236.8 km^2 area to which this applies at the operating water level 70 m above sea level would therefore release 217.8 t/year of methane. The 70-m operating level is specified in the viability study and environmental impact study (EIA) for the dam; the level used in the Project Design Document (PDD) for the carbon project was 70.5 m. With the recently approved increase to 71.3 m above sea level the area would be 272.2 km^2 based on information in the EIA (FURNAS et al. 2005, Tomo A, Vol. 1, p. VII-54; FURNAS and CNO 2007, pp. 125-126), and the emission would be 250.4 t/year.

The area figures given above do not adjust for the loss of reservoir area when the Jirau Dam was moved 9 km downstream, but the difference in emission would be quite small relative to other sources. Note that the Project Design Document (PDD) for the Santo Antônio carbon project, which was submitted after the location of the Jirau Dam had been moved, gives 354.4 km^2 as the reservoir area at the 70.5-m water level (Santo Antônio Energia S.A. 2011, p. 35), or 22.7% higher than the area at this water level given in the EIA. The reservoir was operating at 70.5 m as of April 2014, and the 17 turbines that had been installed by then did not required the additional head from the 71.3 m level.

The tributaries are a much greater source of emission than the body of the reservoir. Unlike the main channel of the river, calculations by the dam proponents indicated that the tributaries would be stratified during all or part of the year (FURNAS and CNO 2007, pp. 150-151). The areas of the three tributaries are: Igarapé Mucuim (Teotonio) 4.55 km^2 at the 70 m water level, 4.92 km^2 at 70.5 m and 5.43 km^2 at 71.3 m; Igarapé Jatuarana 11.11 km^2 at 70 m, 11.53 km^2 at 70.5 m and 12.28 km^2 at 71.3 m; Jaci-Paraná River 18.51 km^2 at 70 m, 20.11 km^2 at 70.5 m and 28.16 km^2 at 71.3 m (FURNAS and CNO 2007, pp. 125-126). These total 34.17 km^2 at 70 m, 38.56 km^2 at 70.5 m and 45.87 km^2 at 71.3 m. The percentage of this area that is covered with macophytes will be a key factor in determining the emission.

Rooted macrophytes (water weeds) represent an important emissions source for methane, as the xylem in their stems provides a direct conduit for gas transfer from the anoxic sediments to the atmosphere. Tropical reservoirs typically experience explosions of macrophyte populations (both rooted and not) in the first years after impoundment, as at Brokopondo in Surinam (Leentvaar 1966), Balbina in Brazil's state of Amazonas (Walker et al. 1999) and Tucuruí in the state of Pará (de Lima et al. 2000). At Tucuruí, for example, a sequence of satellite images indicates that 39% of the reservoir was covered by macrophytes two years after impoundment, after which the cover declined and stabilized at 11% of the reservoir in the tenth year (de Lima et al. 2000). At Santo Antônio an overflight of the reservoir shortly after filling revealed very extensive macrophyte cover (Francisco Pereira, personal communication 2012). It is in the tributaries and in shallow bays along the reservoir edges that macrophytes persist most after the initial flush of macrophyte cover has passed, and it also in these locations where macrophytes are mostly rooted. Measurements of methane fluxes from a macrophyte patch in a tributary to the Santo Antônio reservoir (the Jaci-Paraná River) in February 2012 indicated an emission rate of 127.12 mmol CH_4/m^2/day, considering the concentration in the flux chamber 20 minutes after placement (Note: CH_4 concentrations in flux chambers increase over the course of a standard 30-minute measurement sequence, but, in the case of this measurement, the concentration in the chamber declined to a level corresponding to 36.44 mmol CH_4/m^2/day over the next 10-

minute interval due to a probable break in the seal between the water and the chamber: Grandin 2012, p. 28; Hällqvist 2012, p. 39). The comparable measurement for an adjacent sample without macrophytes was 7.56 mmole/m^2/day. The difference of 119.56 mmole/m^2/day, representing the emission from the macrophytes, is 16 times higher than the emission from the water surface.

If one makes a conservative guess that only 20% of the tributary area is covered with macropytes (i.e., 2.5% of the reservoir as a whole at the 70-m, 2.4% at the 70.5-m level, or 2.9% at the 71.3-m level), then the measured emission of 127.12 mmol CH_4/m^2/day in macrophytes described above implies an emission of 5073.4 t/year at the 70-m level, 5725.2 t/year at 70.5 m and 6810.5 t/year at 71.3 m. The remaining 80% of the tributary surface emitting at 21.1 mmole/m^2/day (SD=16.6, n=3 stations) (Grandin 2012, p. 31) implies an emission of 3367.9 t/year at the 70-m level, 3800.6 at the 70.5-m level and 4521.0 t/year at the 71.3-m level.

Emissions below the dam

In the case of a sampling station located approximately 3 km below the dam (Hällqvist 2012, p. 18), the concentration in the air was 8.4 ppmv, or 5.5 times <u>higher</u> than the concentration found in the water (Grandin 2012, p. 28). Concentrations were also measured at two sampling stations much farther downstream, with mixed results. At a station approximately 29 km below the dam the concentration in the air was only 2 ppmv, while that in the water was 17.5 times higher, or similar to the concentrations in Santo Antônio's tributaries. The other station, located approximately 100 km below the dam, had concentrations similar to those at the station located 3 km below the dam, with a concentration in the air of 13.3 ppmv, or 8.6 times higher than the concentration in the water.

The emission immediately below the dam is of a different type from the emission from the water surface in tributaries within the reservoir. In the case of the tributaries, emission is continuous, with the surface water having high concentrations of CH_4 that is continually replenished by anaerobic decomposition in the sediments below, and the air at 30-cm height above the water has a much lower CH_4 concentration than the water. At the sampling station 3 km below the dam, however, the relationship is reversed, with a greatly enhanced CH_4 concentration in the air, but little in the water. This indicates that, rather than a continuous flux of CH_4 through the water column and diffusion at the surface, the gas has been released in a single burst (presumably mainly of bubbles) as the water emerges from the turbines and spillway. The gas in the air remains over the river for a considerable distance downstream, but the rate of flux at the surface as the water continues to flow downstream would be small – much less than would be needed to explain the elevated concentration of CH_4 at 30 cm height.

Even if the turbulent water in the stretch of river below the dam did not prevent direct flux measurements with chambers, the measurements would tell us little about the amount of CH_4 that had been emitted in the initial burst. Likewise, if data were available on the vertical component of air movement, the total emission could not be calculated from the air concentration because the emission is not a continuous flux. Nevertheless, a very rough idea can be had of a minimum value for this release. It is known from studies of CO_2 concentration profiles in the air column over Amazonian cattle pastures that during the night, if the air is not still, the gas concentration is approximately constant up to a boundary layer height, which, based on two estimation methods, averages 51 m above the surface (Acevedo et al. 2004, p. 893). This refers to a gas (CO_2) coming from a continuous source, namely respiration of the vegetation at night, making it different from a one-time pulse of emission as in the case of CH_4 degassing from the turbines and spillway. The concentration at 30-cm height cannot be extrapolated up to a height of 51 m. However, one can make a conservative assumption, such as that, on average, the air column contains this concentration up to a height of 5 m (i.e., 10% of the approximate height to which the air mass can be assumed to rise at night).

The Madeira River just below the dam has a width of 2.2 km, narrowing to 1.4 km in front of Porto Velho and to 0.8 km below the city (measured from Google Earth). If one assumes that the air mass containing the methane remains over the river course for 6 km (i.e., twice the distance to the first sampling station below the dam, the methane load above the first sampling station therefore representing the half-way point in a presumed linear decline beginning from the dam), and considering the river width of 1.4 km (corresponding to that at the measurement station 3 km below the dam) as most relevant to dissipation of the initial emission from water passing through the dam, the volume of the air mass containing the methane is 4.20×10^7 m^3. Considering the average air temperature of 33 °C at the reservoir measurement sites (Grandin 2012, p. 31), the altitude of the river surface of 55.3 m above sea level (FURNAS et al. 2005, Tomo A, Vol. 1, p. VII-50), the air density at this altitude and temperature is 0.68% less than that at standard temperature and pressure, which is equivalent to 0°C at sea level (Engineering Toolbox 2014).

The average concentration in the air at the four sites on the main reservoir of 1.4 ppmv CH_4 (Hällqvist 2012, p. 27) can be taken as the background concentration for the standpoint of calculating enrichment. The concentration measurements in the air were made at the level of the top of the floating chambers, or approximately 30 cm above the water (Hällqvist 2012, pp. 12-13).

At the temperature and altitude at Porto Velho, one mole of gas occupies 22.55 liters, and the air mass above the river contains 1.86×10^9 moles of air. The methane enrichment of 8.4 – 1.4 = 7.0 ppmv corresponds to 1.30×10^4 moles of methane in the air mass, or 208.6 kg of methane gas. In the month of February, when the methane measurements were made, the prevailing winds at the site are from the north (Cortez 2004, p. 17), meaning that the wind has an angle of attack of 35° with respect to the axis of the river, which (ignoring irregularities) flows in a roughly northeasterly direction in this stretch at an angle of 35° (Google Earth). The average wind speed at the time of the measurement at the sampling station 3 km below the dam was 2.3 m/s (Hällqvist 2012, p. 35). The average wind speed in Porto Velho over the year is 1.4 m/s (Cortez 2004, p. 16). The measured wind speed and the assumed direction imply that the vector representing movement across the river had a velocity of 1.3 m/s. The air over the river was therefore being renewed every 18 minutes, and the total amount of CH_4 emitted corresponded to 27 t/day or 1.67×10^4 t/year.

The total estimated emission from fluxes above and below the dam is 1.48 × 10^4 t/year at the 70-m water level, 1.59 × 10^4 t/year at the 70.5-m level and 1.77 × 10^4 t/year at the 71.3-m level. Of this 41.3% represents downstream emission at the 70-m level, the corresponding percentages being 38.3% for 70.5 m and 34.5% for 71.3 m. The downstream emission is probably primarily from immediate release as the water passes through the dam and would not continue at a significant level from the water surface beyond the measurement point 3 km below the dam.

Some rough reality checks are possible based on the amount of methane that would be transported through the dam at different possible concentrations. Given the 1931-2005 mean streamflow of 18,806 m^3/s, the calculated annual downstream CH_4 emission of 175,024 t represents 15.4% of the 1.14 × 10^6 t/year of methane transported through the dam if the water contained the high mean concentration found in the surface water in the tributaries, but it represents an impossible 410% of the methane passing through the dam (42,730 t/year) if the water contained the concentration measured in surface water in the main river at the closest measurement station above the dam. However, methane concentrations measured at the surface do not represent the average concentration in the water column, especially if the water is stratified, since methane concentrations at the bottom of the reservoir under these conditions are much higher than at the surface. The surface water concentration below the dam being essentially equal to that above the dam means that the methane enrichment of the air is not explained by release of the transported methane as calculated from the surface concentration, and therefore must be from release of methane at higher concentration near the bottom of the river. At the time of the measurement almost all of the river's flow was passing through the spillway, which draws water from deep in the water column and which produces strong turbulence below the dam. A release of this magnitude therefore does not appear unreasonable, but uncertainty is high.

Another check is the percentage of the total methane emission that is estimated to occur downstream, in this case 34.5% for the 70.5-m water level. This percentage is well below those at other dams in tropical South America: Balbina at age 18 years emitted 52.7% of its CH_4 downstream (Kemenes et al. 2007), Petit Saut at age 9 years emitted 78.6% downstream (Abril et al. 2005) and Tucuruí at age 6 years emitted 88.2% downstream (Fearnside 2002). These other dams have significant differences from Santo Antônio, including substantially larger reservoir areas that would lead to a smaller expected importance of downstream emissions as a percentage of the total. The larger streamflow of the Madeira River as compared to the rivers at the other South American dams would also make the expected percentage of downstream emissions greater at Santo Antônio. The lower downstream percentage calculated for Santo Antônio is therefore a feature suggesting that the estimate of downstream emissions is conservative.

I emphasize that the above estimate for Santo Antônio is a very rough calculation, but it gives an idea of the magnitude involved with the best information available. The above estimate contains a variety of conservative assumptions. Perhaps the greatest is that the methane concentration in the air from a measurement made approximately 3 km below the dam represents the value to be applied to the air mass above the river. Because the bulk of emission typically occurs very quickly as the water passes through the dam (see Fearnside and Pueyo 2012), the value used here is probably an underestimate because much of the methane from the initial burst of emission would have already been blown laterally away from the river before reaching the point of measurement.

Dam and transmission line construction emissions

Dam and transmission line emissions are shown in Table S2. The dam construction emissions estimate is conservative, since lack of information results in not including a number of emission sources such as diesel fuel and electricity use. In the transmission line estimate, emissions from production of the 63,000 t of aluminum used in the cables is undoubtedly underestimated, since the emissions from the highly energy-intensive process of aluminum production are calculated from estimates from the Brazilian Association of Aluminum (ABAL 2011) that consider hydropower to be “green” emissions-free energy.

Table S2: Santo Antônio dam and transmission line construction emissions

Category	Item	No. of Items	Amount per item	Total amount	Units	Emission per unit (t CO_2e)	Total emission (t CO_2e)	Amount Reference	Emission Reference
Steel									
	Reinforcing rods			167,837	t			(a)	
	Turbines	44	899.36	39,572	t			(a)	
	Generators	44	234.53	10,319	t			(a)	
	Spillway gates	21	234.53	4,925	t			(b)	
	Other steel			2,500	t			(b)	
	Total steel			225,153	t	2.200	495,336		(c)
Concrete									
	Conventional concrete			3,311,150	t			(a)	
	Roller compressed concrete			408,000	t			(a)	
	Total concrete			3,719,150	t				
	Sand and gravel in concrete			2,769,688	t	0.009	25,758	(d)	(e)
Cement				949,462	t	1.004	953,545	(a)	(e)
Excavation and fill									
	Ordinary excavation			74,364,110	m^3			(a)	(d, f)
	Rock above water			21,554,760	m^3			(a)	(d, f)
	Rock below water			400,000	m^3			(a)	(d, f)
	Earth fill			6,164,780	m^3			(a)	(d, f)
	Rock fill			5,852,870	m^3			(a)	(d, f)
	Rip-rap			1,534,566	m^3			(a)	(d, f)
	Total excavation and fill			109,871,086	m^3	0.0006	68,197		(f)
Dam subtotal							1,542,836		

Transmission line						
Steel	52,000	t	2.200	114,400	(g)	(c)
Aluminum	63,000	t	4.250	267,750	(g)	(h)
Transmission line total				382,150		
Fraction of transmission line attributed to Santo Antônio	0.5					
Transmission line subtotal attributed to Santo Antônio				191,075		
Total attributed to Santo Antônio				1,733,911		

(a) FURNAS and CNO 2008.
(b) Based on Belo Monte (Fearnside 2009).
(c) Van Vate 1995.
(d) Concrete minus cement.
(e) Marheineke nd [1996].
(f) Emissions for "earth haulings" applied to all excavation and fill operations.
(g) Moreira 2013.
(h) ABAL 2011, p. 38.

Comparison of Santo Antônio with baseline emissions

Estimated emissions of Santo Antônio (including downstream emissions) are compared to baseline emissions in Table S3. Table S4 makes the same comparison omitting the very uncertain downstream emissions.

Table S3: Estimated emissions from Santo Antônio (Reservoir at 70.5 m + downstream) compared to baseline emissions

		Baseline emissions (t CO_2e) (a)		Power to be generated (MWh)	Estimated emission from Sto. Antonio			
					CH_4 (t/yr)	GWP=25 (t CO_2e)	GWP=34 (t CO_2e)	GWP=86 (t CO_2e)
Dam construction CO_2 emissions (Table S2)						1,542,836	1,542,836	1,542,836
Dam deforestation CO_2 emissions (Table S2)						6,368,215	6,368,215	6,368,215
Transmission line construction CO_2 emissions attributed to Santo Antônio (Table S2)						191,075	191,075	191,075
Transmission line deforestation CO_2 emissions (Table S1)						252,137	252,137	252,137
Gas-fired power plant construction CO_2 emissions		2157.8	(b)					
0	2012	518,205		1,893,741	15,911	397,782	540,984	1,368,371
1	2013	2,720,189		9,940,726	15,911	397,782	540,984	1,368,371
2	2014	4,953,586		18,102,507	15,911	397,782	540,984	1,368,371
3	2015	5,830,126		21,305,757	15,911	397,782	540,984	1,368,371
4	2016	5,846,099		21,364,129	15,911	397,782	540,984	1,368,371
5	2017	5,830,126		21,305,757	15,911	397,782	540,984	1,368,371
6	2018	5,830,126		21,305,757	15,911	397,782	540,984	1,368,371
7	2019	5,830,126		21,305,757	15,911	397,782	540,984	1,368,371
8	2020	5,846,099		21,364,129	15,911	397,782	540,984	1,368,371
9	2021	5,830,126		21,305,757	15,911	397,782	540,984	1,368,371
10	2022	2,429,219		8,877,398	15,911	397,782	540,984	1,368,371
Total		51,466,185		188,079,300	175,024	12,729,868	14,305,086	23,406,345
Transmission loss to São Paulo(c)		10,293,237	(d)	37,615,860				
Power delivered to São Paulo		41,172,948		150,463,440				
Emission per MWh delivered to São Paulo (t CO_2e/MWh)		0.27				0.08	0.10	0.16

(a) Baseline emissions (Santo Antônio Energia S.A. 2011, p. 35) are based on the Combined Margin Emissions Factor of 0.31, which is 50% from the Grid Operating Margin Emissions Factor (0.4796) and 50% from the Grid build margin emissions factor (0.1404) (Santo Antônio Energia S.A. 2011, p. 34).

(b) Based on the 230-t Alstom GT24 gas turbine, considered state-of-the-art; this 700-MW capacity turbine operates with a 60% power factor

(Wheeler 2012). This would supply a total of 62,362,000 MWh over a period of 10 years, and 4.1 of these turbines would supply the electricity Santo Antônio will deliver to São Paulo.

(c) Assumes 20% transmission loss, the mean for Brazilian losses (Rey 2012). This is conservative for a line of this length.

(d) Although gas-fired plants are built where electricity is used, thereby avoiding transmission loss, the amount of electricity used for calculating baseline emissions in the PDD is based on power delivered to the grid 5 km from the Santo Antônio Dam.

Table S4: Estimated emissions from Santo Antônio (Reservoir only, 70.5 m water level) compared to baseline emissions

		Baseline emissions (t CO_2e) (a)		Power to be generated (MWh)	Estimated emission from Sto. Antonio			
					CH_4 (t/yr)	GWP=25 (t CO_2e)	GWP=34 (t CO_2e)	GWP=86 (t CO_2e)
Dam construction CO_2 emissions (Table S2)						1,542,836	1,542,836	1,542,836
Dam deforestation CO_2 emissions (Table S1)						6,368,215	6,368,215	6,368,215
Transmission line construction CO_2 emissions attributed to Santo Antônio (Table S2)						191,075	191,075	191,075
Transmission line deforestation CO_2 emissions (Table S1)						252,137	252,137	252,137
Gas-fired plant construction CO_2 emissions		2157.8	(b)					
0	2012	518,205		1,893,741	9,816	245,409	333,756	844,207
1	2013	2,720,189		9,940,726	9,816	245,409	333,756	844,207
2	2014	4,953,586		18,102,507	9,816	245,409	333,756	844,207
3	2015	5,830,126		21,305,757	9,816	245,409	333,756	844,207
4	2016	5,846,099		21,364,129	9,816	245,409	333,756	844,207
5	2017	5,830,126		21,305,757	9,816	245,409	333,756	844,207
6	2018	5,830,126		21,305,757	9,816	245,409	333,756	844,207
7	2019	5,830,126		21,305,757	9,816	245,409	333,756	844,207
8	2020	5,846,099		21,364,129	9,816	245,409	333,756	844,207
9	2021	5,830,126		21,305,757	9,816	245,409	333,756	844,207
10	2022	2,429,219		8,877,398	9,816	245,409	333,756	844,207
Total		51,466,185		188,079,300	107,980	11,053,763	12,025,583	17,640,543
Transmission loss to São Paulo(c)		10,293,237	(d)	37,615,860				
Power delivered to São Paulo		41,172,948		150,463,440				
Emission per MWh delivered to São Paulo (t CO_2e/MWh)			0.27			0.07	0.08	0.12

(a) Baseline emissions (Santo Antônio Energia S.A. 2011, p. 35) are based on the Combined Margin Emissions Factor of 0.31, which is 50% from the Grid Operating Margin Emissions Factor (0.4796) and 50% from the Grid build margin emissions factor (0.1404) (Santo Antônio Energia S.A. 20121p. 34).

(b) Based on the 230-t Alstom GT24 gas turbine, considered state-of-the-art; this 700-MW capacity turbine operates with a 60% power factor (Wheeler 2012). This would supply a total of 62,362,000 MWh over a period of 10 years, and 4.1 of these turbines would supply the electricity Santo Antônio will deliver to São Paulo.

(c) Assumes 20% transmission loss, the mean for Brazilian losses (Rey 2012). This is conservative for a line of this length.

(d) Although gas-fired plants are built where electricity is used, thereby avoiding transmission loss, the amount of electricity used for calculating baseline emissions in the PDD is based on power delivered to the grid 5 km from the Santo Antônio Dam.

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APPENDIX E: Explanation of PDD additionality calculation

Half of the Weighted Average Cost of Capital (WACC) value is represented by the cost of debt (calculated to be 3.39%), and the other half is the cost of capital, which is calculated at 17.31% by adjusting a Risk-free rate of 4.88% for an Equity risk premium of 6.57%, which is increased by multiplying by a Sectorial Risk (β) value of 1.34), a country risk premium of 6.06%, and expected US inflation of 2.39% (Santo Antônio Energia, S.A. 2011, p. 14).

The PDD (Santo Antônio Energia, S.A. 2011, pp. 13-14) calculates the WACC of the hydropower sector for 2007 using Equation 1.

$$WACC = (Wd \times Kd) + (We \times Ke) \qquad \text{(eq. 1)}$$

Where:

We = weight of equity typically observed” in the hydropower sector: 50%

Wd = weight of debt “typically observed” in the hydropower sector: 50%

Kd is the cost of debt in the hydropower market; this includes adjustments for the tax benefits of contracting debts. Kd is calculated from Equation 2.

$$Kd = [1 + (a+b+c) \times (1-t)]/ [(1+d) -1] \qquad \text{(eq. 2)}$$

Where:
(a) = Financial cost: 9.28%
(b) = BNDES fee: 0.90%
(c) = Spread: 2.00%
(a+b+c) = Pre-Cost of Debt: 12.18%
(t) = Marginal tax rate: 34.00%
(d) = Inflation forecast: 4.50%

From Equation 2, the after-tax Cost of Debt (Kd) is 3.39% per year.

Ke (cost of equity) represents the rate of return for equity investments. Based on the PDD (Santo Antônio Energia 2011, p. 14) as clarified from spreadsheets, it is estimated with Equation 3:

$$Ke = ((Rf + (\beta \times Rm) + Rc) \times (I / d) \qquad \text{(eq. 3)}$$

Where:
(Rf) = Risk-free rate: 4.88%
(Rm) = Equity risk premium = 6.57%
(Rc) = Estimated country risk premium = 6.06%
(β) = Sector Risk = 1.34
(I) = US expected inflation: 2.39%

(d) = Brazilian Inflation forecast: 4.50%
From Equation 3 the Cost of Equity with Brazilian Country Risk is:

$$Ke = (0.0488 + (1.34 \times 0.0657) + 0.0606) \times (0.0239 / 0.0450) = 0.1731$$

or 17.31% per year.

From Equation 1 the Weighted Average Cost of Capital (WACC) is:

$$WACC = (50\% \times 3.39\%)+ (50\% \times 17.31\%) = 10.35\%$$

Reference

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