Hydropower Development in the Brazilian Amazon

Submitted in partial fulfillment of the requirements for
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Doctor of Philosophy
in
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Felipe Aguiar Marcondes de Faria
B.S., Civil Engineering, University of São Paulo
M.S., Water Resources Engineering, University of São Paulo

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DEDICATION

To my wife, Heloisa, and my parents, Nelson and Viviane.
ACKNOWLEDGMENTS

I would like to thank the crucial support and commitment from my advisor, Paulina Jaramillo, during those four years. I also thank the thesis committee Paulina Jaramillo (Chair), Alex Davis, Inês Lima Azevedo, and Sergio Pacca. I would also like to acknowledge the key contributions that the papers’ co-authors made during the dissertation development. Paulina Jaramillo, Alex Davis, Edson Severnini, Nathan Barros, Henrique Sawakuchi, and Jeffrey Richey, all provided critical inputs and assistance for my research.

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ABSTRACT
Hydropower development in the Brazilian Amazon

Brazil plans to meet the majority of its growing electricity demand with new hydropower plants located in the Amazon basin. The government’s energy policy forecasts the construction of 55 GW of installed capacity by 2028, with total investments in the range of 100 and 200 billion reais (30 to 60 billion dollars), and the creation 9,000 km$^2$ of artificial reservoirs. However, the construction and operation of large hydropower plants may affect the environment, the local economy, and the population surrounding those projects. Considering the magnitude of the investments and the potential impacts for the Amazon basin, it is crucial to apply policy analysis techniques to support informed decisions about whether the construction of large hydropower plants in the Amazon is the best alternative to supply the additional electricity that Brazil needs, taking into account economic, social, and environmental costs and benefits. Here, I apply three different quantitative policy analysis techniques to assess three major questions related to the construction of hydropower plants in the Amazon region. First, I study the greenhouse gas emissions from hydropower reservoirs in the Amazon. Second, I explore the local socio-economic impacts of building hydropower plants. Finally, I investigate alternative electricity sources that could replace Amazon hydropower reservoirs by modeling the Brazilian electricity network under five capacity expansion scenarios.
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Abbreviations

AC: Alternation Cycle
AG: Amazonian Geography
AT: Amazonian Tributaries
B: Baseline
C: Carbon
CGE: Cost-impacts of Global Change
CO2: Carbon Dioxide
COP: Carbon Offsetting Programmes
CPA: Climate Protection Agreements
CRC: Carbon Rights Convention
D: Durban Climate Change Conference
DHA: Divided Habitat Approach
DTU: Danish Technical University
EC: Economic Commission for Latin America and the Caribbean
EIA: Environmental Impact Assessment
EPO: Emissions from the cleared vegetation
EPH: Environmental Protection and Habitat
EPN: Electric Power National
EPA: Environmental Protection Agency
ES: Emissions from the cleared vegetation
EST: Energy Systems Transition
EV: Electric Vehicle
F: Flooded
FL: Flooded area
FPA: Fluvial Processes Awareness
FT: Flooded forest
GB: Greenhouse Gas
GEP: Greenhouse Gas Emission Policy
GEO: Global Environment Outlook
GIS: Geographic Information System
GM: Greenhouse Gas Mitigation
HAB: Habitat
HDI: Human Development Index
HMS: Habitat Modification Strategies
I: Inundated
IPCC: Intergovernmental Panel on Climate Change
IPCC-AR4: Climate Change 2007
IPCC-AR5: Climate Change 2013
IPCC-CRS: Common Representative Scenarios
IPCC-SCAR: Special Climate Change Report
IPCC: Intergovernmental Panel on Climate Change
IPCC-AR4: Climate Change 2007
IPCC-AR5: Climate Change 2013
IPCC-SCAR: Special Climate Change Report
IPCC: Intergovernmental Panel on Climate Change
IPPC: Intergovernmental Panel on Climate Change
IS: Inundated soil
IUS: Inundated urban soil
L: Low
LTD: Low Residence Time
LTC: Low Residence Time Capacity
LTS: Low Residence Time Strategies
M: Moderate
MCF: Mediterranean Forest
MHS: Macrohabitat Shift
MTP: Macrohabitat Transition Potential
N: Natural
NLD: Near Linear Distribution
NLH: Near Linear Hydrology
NTR: Near Terminal Reservoir
ND: Near dotted
NDA: Near dotted area
NTD: Near terminal distribution
NTS: Near terminal stream
O: Other
OL: Outer limits
P: Polluted
PES: Polluted Ecosystem
R: Reservoir
RCP: Representative Concentration Pathways
RT: Residence Time
S: Stream
SD: Surface distribution
SDA: Surface distribution area
SDS: Surface distribution soil
SFT: Surface Flow Transition
SHT: Stream Flow Transition
T: Terrestrial
TD: Top-down
TH: Total Hydrological
TLE: Total Lying Emission
TLP: Total Lying Product
TOM: Terrestrial Organic Matter
TR: Terminal Reservoir
TSD: Total Surface Distribution
TSP: Total Surface Product
U: Urban
UPL: Urban Plan
V: Vegetation
VAC: Virtual Ancestral Catchment
VGP: Virtual Granmother Plant
VLS: Virtual Line Source
W: Wetland
WTP: Water Transfer Potential
X: Xanthocyparis
Xth: Xanthocyparis thujoides
Z: Zone
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1. INTRODUCTION

Since the middle of the 20th century, Brazil has been supplying most of its growing electricity demand by building large hydropower plants. Currently, hydropower plants larger than 30 MW comprise 61% of the total installed capacity (145 GW), and the latest Brazilian government energy plans indicate that an additional 55 GW of hydropower plants will be required to satisfy the electricity demand by 2028. Fossil fuel power plants comprise 28% of the total installed capacity in 2015. Approximately 80% of such new hydropower capacity is expected to be sited over the Amazon basin. The Amazon basin is the focus of the recent hydropower development because the region encloses the last frontier of rivers with abundant hydropower resources that have not been developed yet. The hydropower development policy in the Amazon will require investments that range from 100 to 200 billion reais (30 to 60 billion dollars) and will lead to the creation of around 9,000 km² of artificial reservoirs over the Amazon.

Figure 1-1 describes the spatial distribution of hydropower plant sites that have been registered in the Brazilian electric agency from 2000 to 2012 and includes hydropower plants recently built, under construction, or at designing/licensing stages. The hydropower development in the Brazilian Amazon is a sensitive issue because building reservoirs over the Amazon forest could have several environmental, social, and economic impacts. The consequences of creating artificial reservoirs over rivers and lands have been discussed throughout the scientific literature and include: flooding of agricultural land; loss of terrestrial and aquatic ecosystems; fish migration interruption; change in the biogeochemical cycles affecting nutrient balance, oxygen levels, thermal conditions and sediment flow patterns; greenhouse gas emission associated with
the degradation of the biomass within the reservoirs; the dissemination of waterborne diseases by producing a favorable environment for vectors; loss of cultural / historical heritages; population resettlement; and changes in economic activities and social cohesion.

Despite the important environmental, social, and economic impacts from hydropower development, there are still several questions that should be studied about whether developing so many artificial reservoirs over the Amazon is the most cost-effective option to satisfy the future electricity demand in Brazil. In this dissertation, I applied quantitative policy analysis methods to answer three major questions related to the hydropower development policy in the Amazon.

Figure 1-1: Spatial distribution of hydropower plants in the Legal Amazon. The figure includes hydropower plants in operation, under construction or earlier designing/licensing stages registered in the Brazilian electric agency between 2000 and 2012.
In Chapter 2, I investigate the level of greenhouse gas emissions from recent and future Amazon hydropower plant reservoirs. Under the climate mitigation change efforts, this is a key question because the literature showed that reservoirs built over tropical and forest regions have the potential to produce greenhouse gas emissions of the same order of magnitude than fossil fuel power plants. Carbon dioxide and methane emissions from hydropower result from the oxic/anoxic decomposition of the flooded organic matter (OM) from different sources within the reservoir. In Chapter 2, I develop a method based on a Monte Carlo simulation to predict future emissions from Amazon reservoirs and I apply the method on eighteen new and planned hydropower plants.

In Chapter 3, I study the local economic and social impacts of constructing and operating hydropower plants in Brazil. According to recent environmental impact studies produced to support the licensing processes from Amazon hydropower plants, hydropower development will contribute to the boost the economic activity of counties surrounding the reservoir and thus improving social welfare. Here, I explore whether the positive economic and social impact predicted to the Amazon projects occurred in past projects. I apply econometric and statistical techniques to compare counties that built hydropower between 1991 and 2010 with control counties that had plans to build the power plants but the construction did not materialized.

The Brazilian government official energy plans do not assess alternatives to the construction of Amazon hydropower plants. The government plans assume that large hydropower plants present the most cost-effective alternative to fulfill most of the future electricity requirements. In Chapter 4, I explore alternatives to the construction of hydropower plants in the Amazon by creating alternative electricity expansion plans where wind and natural gas power plants replaces the new hydropower capacity. I employ a dispatch optimization tool to
simulate the Brazilian integrated electric system, and compare the technical, economic, and environmental characteristics of the baseline scenario, which is heavily based on Amazon hydropower, against the alternative plans.

The forest biome of Amazonia is one of Earth’s greatest biological treasures and a major component of the Earth system. The Amazon is also home of thousands of Brazilian Indians tribes and traditional river-dweller communities, embracing a rich cultural and historical heritage. My research has the main objective to employ quantitative policy analysis techniques to improve the stakeholders’ knowledge about the positive and negative impacts from building hydropower in the Amazon, and thus support decision-making. Given the increase in electricity demand in developing countries, the Brazilian context provides important insights for policymaking in the developing world.
2. ESTIMATING GREENHOUSE GAS EMISSIONS FROM FUTURE AMAZONIAN HYDROELECTRIC RESERVOIRS


2.1 Introduction

The Brazilian energy plan states that, by 2022, 85% of new hydropower generation capacity (40 gigawatts) will come from hydroelectric power plants, set to be located in the Amazon region. Supporters of this expansion claim that, among other benefits, hydropower is a low carbon source of electricity. However, this idea has come under scrutiny, particularly for tropical forests reservoirs. Specific hydropower reservoirs in the Amazon were reported to emit greenhouse gases (GHG) of the same order of magnitude as thermal power plants.

One of the major issues that contribute to the controversy about GHG emissions from hydropower is the lack of established method to estimate future emissions. While there are estimates of carbon (C) emissions from specific hydropower reservoirs in tropical forests and their effect on the regional and global C budget, previous work did not present methods to evaluate future emissions. Moreover, although the literature about the C balance in reservoirs has advanced considerably in the last decades, predicting the C budget for future reservoirs is still challenging because of the difficulty in representing the spatial and temporal variability of the C fluxes. Given the high number of dams planned in the Amazon region and in other countries like China, it is imperative to develop models to estimate the C balance of large hydropower projects in order to support decision-making before the dam construction.
The GHG flux rates into the atmosphere from a tropical reservoir depend on a complex combination of physicochemical, meteorological, and reservoir features\textsuperscript{3-5,7-9,11,15,16}. Part of the difficulty of quantifying the C balance spatial and temporal variability of future reservoirs resides in an incomplete understanding of the physical, chemical, and biological processes involved in the production, consumption, and C outgas from reservoirs\textsuperscript{14}. For example, GHG production rate and C fate from flooded trunks is still undetermined\textsuperscript{17}.

Under this context of high uncertainty related to the C balance modeling, this chapter presents a set of models, based on a Monte Carlo simulation structure, to explore the GHG emissions in tropical forested reservoirs. We investigate the GHG emission from new Amazon reservoirs using two approaches: top-down (TD) and bottom-up (BU). The TD approach is based on carbon dioxide (CO\textsubscript{2}) and methane (CH\textsubscript{4}) flux data measured in reservoirs and rivers located in the Amazon region. The BU approach relies on a degradation model based on the available carbon stock within the reservoir area. We then compare our results to the GHG emissions that would occur with other electricity generation sources.

2.2 Data and Methods

2.2.1 GHG emissions from reservoirs and modeling overview

CO\textsubscript{2} and CH\textsubscript{4} emissions from hydropower result from the oxic/anoxic decomposition of the flooded organic matter (OM) from different sources within the reservoir (e.g. vegetation and soils, macrophytes, and algae produced in the reservoirs) and from outside the reservoir (e.g. sedimentary OM input from the upstream river basin)\textsuperscript{8,17,18}. CO\textsubscript{2} is formed by bacterial respiration of OM in the soils, sediments, and water column but is also imported from upstream
and lateral sources, such as drawdown zones\textsuperscript{17}. Further, CO\textsubscript{2} in freshwaters is produced by respiration and decomposition and assimilated by aquatic primary production\textsuperscript{19}. CH\textsubscript{4} is produced in the reservoir’s anaerobic zones by methanogenic bacteria, and can then be oxidized into CO\textsubscript{2} by methanotrophic bacteria in both the soils’ aerobic zones\textsuperscript{17,20} and the water column\textsuperscript{21,22}.

After production, CO\textsubscript{2} and CH\textsubscript{4} are released into the atmosphere through four major pathways:

1. **Diffusion in the reservoir area**, which is the flux that occurs in the air-water interface of the reservoir due to the difference in gas concentrations at this layer\textsuperscript{23}.

2. **Ebullition in the reservoir area** that results from the quick release of GHG from sediment pore waters supersaturated with CH\textsubscript{4}\textsuperscript{24}.

3. **Outlet degassing** that results from pressure and temperature changes that occur on discharge flows just after low-level outlets, such as turbines and spillways\textsuperscript{8,9,11}.

4. **Diffusion and ebullition downstream of the dam**, which occur in the river area below the dam and are associated with the high concentrations of GHG from the reservoir hypolimnion\textsuperscript{8,11}.

The net GHG emissions in a river basin resulting from the creation of a reservoir should account for the balance between emissions and sinks in all parts of the watershed affected by the reservoir before and after the impoundment\textsuperscript{5,9,16,25}. To estimate net GHG emissions for the first 100 years of operation we employed two approaches.

First, the TD approach relies on GHG flux data measured in tropical Amazonian reservoirs (Balbina, Petit Saut, Tucuruí, Samuel, and Santo Antônio) and rivers, which were used to model the various emission components: diffusion and bubbling from the reservoir, outlet degassing, diffusion and ebullition from downstream, and the natural river. Therefore, this model
directly accounts for the major emission pathways into the atmosphere, and the difference between emissions before and after the reservoir flooding defines the net reservoir emissions.

Second, the BU approach is based on the potential emissions derived from the degradation of the flooded OM in the reservoir area, accounting for GHG production rates and CH$_4$ oxidation in the water column. Brazilian environmental rules require vegetation clearing of the flooded area before filling the reservoir$^{26}$. However, biomass regrowth and inefficient clearing may increase the flooded C stock. In the BU approach, the net reservoir emissions are defined as the difference between 1) the CO$_2$ and CH$_4$ production from the degradation of the flooded C stocks (soils and remaining foliage), and 2) the CH$_4$ consumption and CO$_2$ production in the freshwater system by CH$_4$ oxidation. The BU model also accounts for the emissions from the vegetation that is cleared, which decays within the time horizon of this analysis.

In our framework, we assigned probability distributions for each of the uncertain variables in the models. Based on independent sampling from these distributions, each simulation corresponds to the computation of a model outcome. We applied the models to new Amazon hydropower reservoirs, repeating each simulation 10,000 times.

### 2.2.2 Residence time, stratification, and GHG emissions

Reservoir stratification occurs as a result of thermal differentials in the water column that prevent vertical water mixing. The reservoir stratification with an anoxic bottom layer creates the conditions for CH$_4$ accumulation in the hypolimnion$^{3,8}$. Old Amazonian reservoirs (Balbina, Samuel, Petit Saut and Tucurui), where the GHG flux data that are the basis for the TD model were measured, stratify for long periods (several months) with intervals of complete mixing. The biogeochemical cycles in these reservoirs are strongly related to the decomposition of vegetation and anoxic conditions in the hypolimnion$^{27}$. 
Previous work has described the stratification process and its relation to residence time (RT), which is defined by the time that a molecule of water remains in the reservoir (see Appendix A, section 6.1.1.3). Typical lake stratification occurs in reservoirs with high RT (>100 days). This trend is consistent with the conditions at the Petit Saut reservoir, where there is a high positive correlation between RT, CH$_4$ concentrations, and emissions. Further, the high levels of CH$_4$ concentrations in the hypolimnions are highly correlated with outlet degassing and downstream emissions. The main channel of reservoirs with low RT (<10 days), on the other hand, have characteristics that resemble a river zone: a completely mixed water column, with homogenous flow rate and temperature distribution. This trend is consistent with the conditions in Santo Antônio reservoir. However, tributary and bay zones in low RT reservoirs may present different conditions and stratify because of lower water flows in these areas. Moreover, CH$_4$ oxidation efficiency also depends on the characteristics of the water column, such as light penetration, turbulence, and reservoir depth. Therefore, GHG fluxes in new Amazonian reservoirs will depend on their stratification level.

### 2.2.3 New Amazonian hydroelectric reservoirs

We assessed CO$_2$ and CH$_4$ emissions of 18 reservoirs recently built, under construction, or planned in 8 rivers in the Amazon basin, corresponding to a total of 5,900 km$^2$ of reservoir area and a total installed capacity of 40 GW (Table 2-1). The design characteristics of the hydropower plants come from engineering reports provided by the Brazilian Electric Agency (Agência Nacional de Energia Elétrica – ANEEL). For each reservoir, we then cross-referenced the spatial location data of the reservoir shape with high-resolution maps of land surface, permanent water bodies, and forest biomass density in order to estimate the reservoir and river...
areas, and the biomass C stock in the reservoir area\textsuperscript{33,34}. Appendix A (see section 6.2) provides a detailed explanation of the method used to estimate the reservoir and river areas.

Table 2-1: Characteristics of hydroelectric reservoirs included in this study. Table S8 in the Appendix A present the detailed data source from ANEEL for each project.

<table>
<thead>
<tr>
<th>Hydroelectric Power Plant</th>
<th>River</th>
<th>Power (MW)</th>
<th>Capacity Factor</th>
<th>Reservoir Area: (km\textsuperscript{2})</th>
<th>Reservoir Operation</th>
<th>Volume (x10\textsuperscript{6} m\textsuperscript{3})</th>
<th>Mean Flow (m\textsuperscript{3}/s)</th>
<th>Mean Depth (m)</th>
<th>Power Density (MW/km\textsuperscript{2})</th>
<th>Water Type*</th>
</tr>
</thead>
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<tr>
<td>Belo Monte</td>
<td>Xingu</td>
<td>11233</td>
<td>0.41</td>
<td>516</td>
<td>run-of-river</td>
<td>4570</td>
<td>7800</td>
<td>9</td>
<td>21.8</td>
<td>Clear</td>
</tr>
<tr>
<td>Bem Querer</td>
<td>Branco</td>
<td>708</td>
<td>0.55</td>
<td>559</td>
<td>run-of-river</td>
<td>2530</td>
<td>3000</td>
<td>5</td>
<td>1.3</td>
<td>Clear</td>
</tr>
<tr>
<td>Cachoeira do Cai</td>
<td>Jamaxim</td>
<td>802</td>
<td>0.51</td>
<td>420</td>
<td>storage</td>
<td>3420</td>
<td>1940</td>
<td>8</td>
<td>1.9</td>
<td>Clear</td>
</tr>
<tr>
<td>Cachoeira do Caldeirão</td>
<td>Araguari</td>
<td>219</td>
<td>0.56</td>
<td>48</td>
<td>run-of-river</td>
<td>231</td>
<td>930</td>
<td>5</td>
<td>4.6</td>
<td>Clear</td>
</tr>
<tr>
<td>Cachoeira dos Patos</td>
<td>Jamaxim</td>
<td>528</td>
<td>0.32</td>
<td>117</td>
<td>storage</td>
<td>696</td>
<td>1330</td>
<td>6</td>
<td>4.5</td>
<td>Clear</td>
</tr>
<tr>
<td>Colider</td>
<td>Teles Pires</td>
<td>300</td>
<td>0.56</td>
<td>172</td>
<td>run-of-river</td>
<td>1520</td>
<td>943</td>
<td>9</td>
<td>1.7</td>
<td>Clear</td>
</tr>
<tr>
<td>Ferreira Gomes</td>
<td>Araguari</td>
<td>252</td>
<td>0.60</td>
<td>18</td>
<td>run-of-river</td>
<td>137</td>
<td>963</td>
<td>8</td>
<td>14.2</td>
<td>Clear</td>
</tr>
<tr>
<td>Jamaxim</td>
<td>Jamaxim</td>
<td>881</td>
<td>0.53</td>
<td>74</td>
<td>storage</td>
<td>1000</td>
<td>1370</td>
<td>13</td>
<td>11.8</td>
<td>Clear</td>
</tr>
<tr>
<td>Jatobá</td>
<td>Tapajós</td>
<td>2338</td>
<td>0.55</td>
<td>646</td>
<td>storage</td>
<td>4010</td>
<td>10400</td>
<td>6</td>
<td>3.6</td>
<td>Clear</td>
</tr>
<tr>
<td>Jirau</td>
<td>Madeira</td>
<td>3750</td>
<td>0.58</td>
<td>303</td>
<td>run-of-river</td>
<td>2750</td>
<td>17900</td>
<td>9</td>
<td>12.4</td>
<td>White</td>
</tr>
<tr>
<td>Marabá</td>
<td>Tocantins</td>
<td>1850</td>
<td>0.63</td>
<td>1,024</td>
<td>run-of-river</td>
<td>5350</td>
<td>10300</td>
<td>5</td>
<td>1.8</td>
<td>Clear</td>
</tr>
<tr>
<td>Salto Augusto de Baixo</td>
<td>Juruenia</td>
<td>1461</td>
<td>0.54</td>
<td>125</td>
<td>run-of-river</td>
<td>362</td>
<td>4120</td>
<td>3</td>
<td>11.7</td>
<td>Clear</td>
</tr>
<tr>
<td>Santo Antônio</td>
<td>Madeira</td>
<td>3150</td>
<td>0.65</td>
<td>271</td>
<td>run-of-river</td>
<td>2080</td>
<td>18200</td>
<td>8</td>
<td>11.6</td>
<td>White</td>
</tr>
<tr>
<td>São Luis do Tapajos</td>
<td>Tapajós</td>
<td>6133</td>
<td>0.52</td>
<td>722</td>
<td>storage</td>
<td>7550</td>
<td>11900</td>
<td>10</td>
<td>8.5</td>
<td>Clear</td>
</tr>
<tr>
<td>São Manoel</td>
<td>Teles Pires</td>
<td>746</td>
<td>0.49</td>
<td>64</td>
<td>run-of-river</td>
<td>577</td>
<td>2260</td>
<td>9</td>
<td>11.7</td>
<td>Clear</td>
</tr>
<tr>
<td>Sao Simão Alto</td>
<td>Juruenia</td>
<td>3509</td>
<td>0.55</td>
<td>284</td>
<td>run-of-river</td>
<td>3820</td>
<td>4190</td>
<td>13</td>
<td>12.4</td>
<td>Clear</td>
</tr>
<tr>
<td>Sinop</td>
<td>Teles Pires</td>
<td>461</td>
<td>0.43</td>
<td>330</td>
<td>storage</td>
<td>3070</td>
<td>894</td>
<td>8</td>
<td>1.4</td>
<td>Clear</td>
</tr>
<tr>
<td>Teles Pires</td>
<td>Teles Pires</td>
<td>1820</td>
<td>0.54</td>
<td>152</td>
<td>run-of-river</td>
<td>905</td>
<td>2410</td>
<td>6</td>
<td>12.0</td>
<td>Clear</td>
</tr>
</tbody>
</table>

The water type classification is based on the map elaborated by Junk et. al (2011)

2.2.4 Model details

Two stages characterize the C emissions from hydroelectric reservoirs. During the first stage, decomposition of easily degradable biomass in the flooded area (like soil micro fauna and
green parts of the vegetation) drives a sharp increase in emissions during the first few years. During the second phase, emissions tend to be slower as the system reaches a steady state\textsuperscript{3,5,12,18}.

To account for the influence of water column conditions on reservoirs emissions, we developed separate TD models for stratified reservoirs (high RT) and well-mixed reservoirs (low RT) in our database. To assess the stratification level of each reservoir, we performed an analysis of the Densimetric Froude number, which is a more accurate criterion for the development of stratification compared to the RT alone\textsuperscript{29} (see Appendix A, section 6.1.1.3, for more details). We classified the characteristics of each reservoir according to their operating characteristics, RT, and propensity to stratify. Based on this analysis, which we described in more detail in the Appendix A, we find that Cachoeira dos Patos, Cachoeira do Cai, Sinop, and Jamanxim are reservoirs with high RT and long periods of stratification, and they are assumed to behave similarly to the older reservoirs from which C flux data have been collected. All the other reservoirs in our database have well-mixed water columns with low RT throughout the year, and the main channel will thus resemble the emissions of natural rivers. Tributaries and bays in these low RT reservoirs, however, stratify and thus result in emissions that are similar to those of the high RT reservoirs.

The BU model, on the other hand, relies on a degradation model based on the flooded and cleared C stock in the reservoir area. Table 2-2 provides a summary of the models’ variables and major assumptions.
Table 2-2: Summary of the modeling assumptions.

<table>
<thead>
<tr>
<th>Uncertain Variables</th>
<th>Major Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bottom up</strong></td>
<td></td>
</tr>
<tr>
<td>• Flooded carbon stock in the soils and foliage</td>
<td>We assumed a uniform distribution that varies from 8 to 16 Gg C/km² for 0-20 cm layer to define the carbon stock in the soils⁵. We also assumed that an inefficient biomass clearing contributes to an additional flooded carbon stock from foliage that varies from 0.6 to 6.4 C/km²³⁶.</td>
</tr>
<tr>
<td>• Carbon stock from cleared biomass</td>
<td></td>
</tr>
<tr>
<td>• CO₂/CH₄ Production</td>
<td></td>
</tr>
<tr>
<td>• CH₄ Oxidation</td>
<td></td>
</tr>
<tr>
<td>• CO₂ Production from CH₄ oxidation (Bacteria Efficiency Growth)</td>
<td></td>
</tr>
<tr>
<td><strong>Top-down</strong></td>
<td></td>
</tr>
<tr>
<td><strong>High RT</strong></td>
<td></td>
</tr>
<tr>
<td>• Reservoir Diffusion and Ebulition</td>
<td>Based on emissions fluxes from classical “old” reservoirs of Tucurui, Petit Saut, Samuel, and Balbina, which have high RT and present long periods of stratification throughout the year⁸,¹⁰,¹¹,¹⁵,³⁸.</td>
</tr>
<tr>
<td>• Outlet Degassing</td>
<td></td>
</tr>
<tr>
<td>• Downstream Diffusion and Bubbling</td>
<td></td>
</tr>
<tr>
<td>• Natural Emissions</td>
<td></td>
</tr>
<tr>
<td><strong>Low RT</strong></td>
<td></td>
</tr>
<tr>
<td>• Reservoir Diffusion and Bubbling</td>
<td>We divided the reservoir area in two regions:</td>
</tr>
<tr>
<td>• Natural Emissions</td>
<td>• The main channel zone has well-mixed water columns and limnological characteristics similar to river zones. Therefore, the probability distributions adopted for the reservoir fluxes in this model rely on the fluxes data from large natural rivers in the Amazon.</td>
</tr>
<tr>
<td>• Degassing/Downstream (parametrically)</td>
<td>• The bays and tributaries zones have stratified conditions and probability distributions used are based on the emissions fluxes from classical “old” reservoirs.</td>
</tr>
<tr>
<td></td>
<td>Degassing/downstream emissions in these reservoirs are based on Santo Antônio reservoir data³¹. We treated this pathway parametrically because only one estimate is available. See the Appendix A for details.</td>
</tr>
</tbody>
</table>

**Bottom-up approach.** We present a mass balance to estimate net reservoir emission using CO₂ and CH₄ production rates derived from incubation of soils and foliage from the Petit Saut reservoir¹⁷. The initial flooded C stock is defined by the multiplication of the flooded area (discounting the natural river area) and the soil/foliage OM C density. Additionally, we account for the fate of the cleared biomass C stock for each reservoir based on above the ground biomass
distribution map\textsuperscript{34}. We assumed that C of the cleared biomass decays in a period of 30 years and is released to the atmosphere as CO\textsubscript{2} (See Appendix A, section 6.4.2, for a more detailed discussion about the fate of cleared biomass).

We calculated GHG production using monthly times steps and production rates sampled from distributions based on the mean and standard deviation of GHG potential production rates obtained from soil/foliage incubation from Petit Saut reservoir\textsuperscript{17}. We assumed that CH\textsubscript{4} production rates are the same for both low and high RT models because most of the organic C in the saturated soil/water layers is expected to be in similar anoxic environments. CH\textsubscript{4} oxidation is treated as a fraction of the CH\textsubscript{4} produced from soils/foliage (See Table 2-2). CH\textsubscript{4} oxidation results in CO\textsubscript{2} production and we assume that bacterial growth efficiency has a triangular distribution that ranges from 10% to 80% with the most probable value at 50%.

\textit{Top-down approach.} In the top-down approach, we divided the GHG emissions in two systems: the river system (before flooding) and the reservoir system (after flooding). Using reservoir shape data, we identified the beginning of the reservoir at the upstream side (upstream limit) and extended the model boundary to cover C fluxes that occur up to a 40-kilometer river distance downstream the dam (downstream limit).

The river system represents the environment before the construction of the reservoir; in other words, the model accounts for the natural fluxes in Amazonian rivers. Rivers and wetlands in the Amazon are natural C sources as they transport, respire, and outgas C originating from organic matter from upland and flooded forests. For this study, we performed a meta-analysis of published CO\textsubscript{2} and CH\textsubscript{4} fluxes in Amazon rivers\textsuperscript{39-44} and classified the measurements by spatial location, water-chemistry type, and river size. Based on this database, we fitted statistical distributions to represent the variability of GHG fluxes in large Amazon Rivers (width greater
than 100 meters) according to water type: black water is associated with a high content of humic compounds; white water is associated with a high content of suspended sediment; and clear water is characterized by the lack of turbidity caused by sediments and a dark color caused by humic compounds\textsuperscript{45,46}.

The reservoir system characterizes the environment after the construction of the dam and consists of reservoir surface, degassing, and downstream fluxes. The differences in the fluxes into the atmosphere between the reservoir system and the river system define the reservoirs’ net GHG emissions. We estimated CO\textsubscript{2} and CH\textsubscript{4} emissions for both systems. Using available data (described in Table 2-3), we fit several distribution functions to represent the flux rates’ uncertainty and variability for each of the modeled pathways. Appendix A (section 6.3) provides detailed information about these distributions and data points.

The flux data we used in this study was collected years after the reservoirs started operations, so we assumed that our sample represents the behavior of the reservoir system in a steady state. We also assumed that natural rivers are in a steady state of emissions. We then chose the best distribution for each flux rate through the calculation of the Bayesian Information Criterion and Akaike Information Criterion\textsuperscript{47}. We multiplied the specific flux and the associated surface area to define the total annual fluxes of CO\textsubscript{2} and CH\textsubscript{4} for each emissions pathway. Based on the emissions profile measured at Petit Saut in the first ten years of operation, we then modeled the first pulse of emissions by applying a multiplier factor to the steady state emissions for the reservoir system (three times for the first three years, and two times for the fourth and fifth years). Finally, we converted CH\textsubscript{4} emissions to the equivalent CO\textsubscript{2} emissions using the 20 and 100 year CH\textsubscript{4} global warming potential of 86 and 34, respectively\textsuperscript{27,48}. Appendix A includes the detailed mathematical formulation of the models.
Table 2-3: Summary of flux data (n = data points). Details of each data point are described in Appendix A (section 6.3)

<table>
<thead>
<tr>
<th>Emission Source</th>
<th>mg CH₄ m⁻² d⁻¹</th>
<th>mg CO₂ m⁻² d⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>Rivers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>10</td>
<td>0-160</td>
</tr>
<tr>
<td>Clear</td>
<td>70</td>
<td>2-650</td>
</tr>
<tr>
<td>Black</td>
<td>10</td>
<td>0-53</td>
</tr>
<tr>
<td>Reservoirs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir</td>
<td>50</td>
<td>0-210</td>
</tr>
<tr>
<td>Degassing</td>
<td>220</td>
<td>50-900</td>
</tr>
<tr>
<td>Downstream</td>
<td>1,100</td>
<td>190-1,800</td>
</tr>
</tbody>
</table>

References:

2.3. Results and Discussion

Figure 2-1 presents the summary of the mean and 95% confidence interval (CI) of net GHG emissions over 100 years that result from 10,000 simulations for each modeling approach for each assessed reservoir. The simulations reveal a high variability of fluxes across the dams as a consequence of the site-specific characteristics of each project (reservoir area, river areas, and water type), as well as modeling assumptions. Mean net GHG emissions for all reservoirs over 100 years vary from 90 Tg of C (CI: 80 – 100) in the BU approach to 340 Tg of C (CI: 210 – 520) in the TD approach.

The emission results from the BU model shown in Figure 2-1 are based on the initial soils and biomass C stock in the reservoir area. They represent lower bound estimates because C inputs from upstream and primary production in the reservoir are not included. Compared to the emissions from soils only, flooded foliage contributes to an average increase in CH₄ and CO₂ emissions of 33% and 28%, respectively. This result demonstrates the importance of the
enforcement and improvement of vegetation clearing as a GHG emissions mitigation measure, as discussed in more detail in the Appendix A (section 6.4.2).
Figure 2-1: Simulation results summary for CH₄ (red) and CO₂ (blue) emissions. These values are in Tera grams (Tg) of Carbon, so they do not include the GWP values for CH₄. Mean net GHG emission over 100 years (circle) and 95% confidence intervals (error bars). Black numbers represent net reservoir emissions: mean and 95% confidence intervals in parenthesis. (*) Indicate high residence time reservoirs (first and second rows). Note that the scale of the y-axis is not consistent across all panels.
2.3.1 Low residence time reservoirs

In the case of the low RT reservoirs, Figure 2-1 shows that mean net GHG emissions over 100 years from the BU model range from 0.1 (CI: 0 – 0.2) Tg of C in Ferreira Gomes to 14 (CI: 10 – 17) Tg of C in Marabá. Mean TD estimates vary from 1 (CI: 0 – 3) Tg of C in Ferreira Gomes to 49 (CI: 5 – 160) Tg of C in Marabá. The BU method is based on a decreasing degradation function for the OM in the soils, residual foliage, and cleared vegetation (fixed initial C stock), while the TD model accounts for fluxes derived from freshwater systems. The TD fluxes were measured in the air-water interface and, thus, also account for other C inputs (e.g. upstream and lateral C inputs, and OM from primary production)\(^8,17,49\). As a result, the mean results in the TD approach are on average 4 times higher than the mean results in the BU approach. Both approaches, however, result in estimates within the same order of magnitude. Average CH\(_4\) emissions have the same order of magnitude for both approaches, but the uncertainty from the TD method is higher due to the characteristics of the statistical distributions adjusted in this model, which are right-skewed and have a long tail. Figure S12 in the Appendix A highlights the contribution of each pathway to the total C budget.

2.3.2 High residence time reservoirs

For high RT reservoirs, the BU approach indicates that the mean net GHG emissions over 100 years vary from 1.8 (CI: 1 – 2) Tg of C in Jamanxim to 11 (CI: 9 – 13) Tg of C in Cachoeira do Caí (Figure 2-1). The mean results in the TD model are one order of magnitude higher compared to the BU outcomes and vary from 11 (CI: 4 – 18) Tg of C in Jamanxim to 30 (CI: 11 – 54) Tg of C in Sinop. Again, this difference is a result of the distinctive methods employed for each approach. The BU model relies on a decreasing degradation function and provides a lower
bound estimate that only accounts for the initial C stock in the reservoir area. In contrast, the TD approach relies on flux data measured in reservoirs where the above the ground biomass was not cleared. Thus, the TD approach accounts for fluxes into the atmosphere that derive from all inputs, including below and above-the-ground C stocks, as well as C imports from upstream and reservoir primary production.

New reservoirs in Brazil can only be filled after vegetation clearing\textsuperscript{26,31}, which did not occur in Petit Saut, Balbina, Tucuruí and Samuel. As a result, while the BU estimates are downward biased (underestimates), the TD approach is upward biased (overestimates) for high RT reservoirs. At this time, we are unable to assess the size of this bias, because we cannot distinguish between flooded, terrestrial, and aquatic inputs and their specific contribution to GHG emissions. This also justifies the use of two modeling approaches; merging them would leads to the risk of double counting. We propose, however, that the BU and TD results provide a range of plausible emissions from these reservoirs.

Figure 2-2 breaks down the contribution of each emission pathway to the net emissions (mean) for the TD approach in high RT reservoirs. For these reservoirs, the gross fluxes from the reservoir system (Figures 2-2A, 2-2C and 2-2E, after flooding) and the natural river system (Figures 2-2B, 2-2D and 2-2F, before flooding). In terms of C mass (Figures 2-2A and 2-2B), CO\textsubscript{2} emissions from the reservoir, downstream emissions, and CO\textsubscript{2} fluxes from the natural river are the largest contributors to C fluxes. On the other hand, when including the 20-year and 100-year GWP as a metric for climate impacts, Figure 2-2C and 2E show that CH\textsubscript{4} emissions account for most of the total Tera grams of CO\textsubscript{2} equivalents. In the mean scenario, natural emissions before the impoundment account for 5% to 30% of the reservoir system emissions (comparing
Figure 2-2A and 2-2B), highlighting the importance of accounting for this natural emission pathway in the net C balance of Amazonian reservoirs.

Figure S12 in Appendix A (section 6.4) shows similar results for the low RT reservoirs. While the magnitude of emissions varies significantly across reservoirs, Figure S12 highlights the same trends observed for high RT reservoirs in Figure 2-2: CH$_4$ emissions after the impoundment and natural emissions are critical components of the net C balance of these reservoirs. The main advantage of low RT reservoirs compared to high RT is the lack of stratification in the main channel. As a consequence, low RT reservoirs have lower average emissions from the reservoirs’ surface in the main channel itself, as well as lower degassing/downstream fluxes. However, the major driver for high total GHG emissions is the size of the reservoir area. For example, Marabá is a low RT reservoir but resulted in the highest total GHG emissions over 100 years, because this reservoir has the greatest reservoir area from our database.
Figure 2-2: Top-down approach mean results for the four high residence time reservoirs in a hundred years by emission pathway. A- Reservoir system in C. B- River System (Natural Emissions) in C. C - Reservoir system in CO₂ eq using the 20-year global warming potential (GWP) value for CH₄. D - River System in CO₂ eq using the 20-year GWP value for CH₄. E - Reservoir system in CO₂ eq using the 100-year GWP value for CH₄. F - River System in CO₂ eq using the 100-year GWP value for CH₄.
2.3.3 Emission factors: hydropower in the Amazon versus other sources of electricity

To compare our results from hydropower plants in the Amazonian basin with other electricity generation sources, we calculated the emission factor for each reservoir in units of kg CO$_2$eq MWh$^{-1}$ (Figure 2-3). As before, the results include the 20-year and 100-year GWP for CH$_4$. We used a meta-analysis from the Intergovernmental Panel on Climate Change (IPCC) with life cycle assessment studies as a reference to compare our results with other sources of electricity$^{50}$. This literature indicates that the median emission factors for natural gas, oil, and coal-based power plants are 470, 840, and 1,000 kg CO$_2$-eq MWh$^{-1}$, respectively$^{50}$. In the case of renewables, the median emission factors are 4, 12, and 46 kg CO$_2$-eq MWh$^{-1}$ for hydropower, solar (photovoltaic) and wind, respectively. This comparison is not meant to be a recommendation about the source of energy Brazil should pursue, as such recommendation requires much more detailed analysis about the entire power system that is beyond the scope of this chapter.

Figure 2-3 shows that six of the reservoirs (Cachoeira do Caí, Cachoeira dos Patos, Sinop, Bem Querer, Colider and Marabá) have a significant number of simulations that result in emission factors that are comparable to those of thermal power plants. The simulation results confirm that using life cycle emission estimates from hydropower currently available in the IPCC report to aid decision-making may result in unintended consequences$^{51}$. 
Figure 2.3: Average emission factors simulation results over 100-years (kg CO$_2$eq MWh$^{-1}$). Results are presented for two methane global warming potential (GWP). GWP20 represent the emission factors assuming GWP equal 86. GWP100 represent the emission factors assuming GWP equal 34. The x-axis plots each of the 10,000 simulation points against a random number generated within a fixed range in the y-axis. Black vertical dashed lines represent median power plant emission factors: hydropower (4), natural gas (470), oil (840) and coal (1,000) $^{58}$. (†) Indicates high residence time reservoirs.
It is noteworthy that Figure 2-3 shows that high RT reservoirs have higher simulated emission factors compared to thermal power plants. Even though we concluded that the TD approach overestimates GHG emissions for new high RT reservoirs, combined with the lower bound estimates from the BU approach, we can gather useful information to understand the potential range of GHG emissions in new reservoirs. For example, the results indicate that Jamanxim reservoir likely has a lower emission factor than thermal power plants, because of the dominance of simulation results below the natural gas power plants reference value. In contrast, most of the simulated emission factors for Cachoeira dos Patos, Cachoeira do Caí, and Sinop are higher than those for thermal power plants.

Moreover, it is worth highlighting that because of the higher GWP for CH₄ over 20 years, the simulation results using this GWP are higher and suggest the hydropower emissions could have serious climate impacts in the short-term. Appendix A presents the emission factor simulation results by reservoir age. During the first three years of operation, all new hydropower plants in the Amazon have at least some emission factor outcomes above or at the natural gas generation level (See Tables S22 and S23 in the Appendix A). While GWP can serve as a proxy for climate impacts, recent studies suggest it can be an imperfect metric for policy analysis. In this study, for example, using GWP implicitly assumes that the emissions over the entire life of these projects (100 years) occur as a pulse emission in year 0. Thus, the values in this study do not account for the timing of emissions. Hence, this study should not be the basis for statements about the global climate impacts of large reservoirs, such as the effect on global temperatures. The results in this study, however, present an account of C emissions that could later be used to model such climate impacts, and future work will expand on this area of research.
Focusing on low RT reservoirs, the reservoirs of Bem Querer, Colider and Marabá have a high number of simulations that suggest these reservoirs have emissions factors larger than those of thermal power plants. In the case of the 20-year results, the emission factors from the BU simulations are also high, consistent with the TD results. Further, Ferreira Gomes is the only reservoir with emission factors that are similar to those of solar and wind projects. In summary, Figure 2-3 shows that a robust treatment of the uncertainty, which is possible by the application of the Monte Carlo simulation structure and the clear statement of model assumptions, provides valuable information about each reservoir that can be used to support decision-making in most cases.

Another relevant difference worth noting between some of the old and new hydropower reservoirs in the Amazon is the relationship between flooded area and installed capacity (power density in MW km\(^{-2}\)). There is a strong negative correlation between the hydropower plant emission factors and its power density\(^5\). Reported emission factors for the old tropical reservoirs of Balbina, Tucurui, Petit Saut, and Samuel are higher than those of fossil fuel power plants, with mean emission factors of 2,200, 480, 1,300, and 2,200 kg CO\(_2\)eq per MWh, respectively\(^5\). The power densities of Balbina, Tucurui, Petit Saut, and Samuel reservoirs are 0.1, 2.9, 0.4 and 0.4 MW km\(^{-2}\), respectively. In contrast to these old reservoirs, 13 of the new projects studied in this study have power densities greater than 3.5 MW/km\(^2\) (See Table 2-1). Not surprisingly, the reservoirs with the lower energy densities are also the projects with higher emissions factors in our estimates (See Figure S13 and S14 in the Appendix A). Additionally, three out of the five storage power plants in our database are in the highest emission factor group because the additional volume for water storage often requires more reservoir area, which leads to lower
energy densities and higher emission factors. Appendix A presents a sensitivity analysis about the effect of the reservoir area in our estimates for storage reservoir.

2.4 Implications and Uncertainty

Our results suggest that GHG emissions from hydroelectric reservoirs vary significantly across the different projects; these emissions could be higher than currently assumed and, under specific conditions, could even be comparable to those of fossil-based power plants. Most of the reservoir simulations resulted in lower emission factors when compared to those of thermal power plants, but higher when compared to those of solar or wind projects. It is important to note that this comparison is based on the accounting of emissions over the life of the projects and is not meant to be an assessment of the actual climate impacts from these energy projects, which would require either the use of more detailed climate metrics than GWP or a climate model.

Nevertheless, the comparison of emission factors between hydropower plants in the Amazon and other sources of electricity suggests that the climate impacts from large scale development of Amazonian hydropower can be greater than has been suggested in the life cycle literature. Over a hundred years, the 18 new reservoirs in the Amazon would lead to a average total emissions that vary from 9 Tg of CH\textsubscript{4} and 81 Tg of CO\textsubscript{2} (BU approach) to 21 Tg of CH\textsubscript{4} and 310 Tg of CO\textsubscript{2} (TD approach). As a point of comparison, emissions from the U.S. natural gas energy system totaled 10 Tg of CH\textsubscript{4} and 35 Tg of CO\textsubscript{2} in 2013 (EPA 2014). As the global community moves to mitigate global GHG emissions, the potential emissions from Amazonian reservoirs should be considered in the context of emissions from other alternatives.

The Brazilian government is currently evaluating whether to keep investing in low RT reservoirs due to the advantages of adding storage capacity to the electric system. The results in
this chapter suggest that the adoption of high energy density reservoirs contributes to reduce overall GHG emissions for hydropower plants. Thus, the proposal to shift towards construction of storage reservoirs with larger areas and higher RT could result in increased emissions from Amazonian projects. Furthermore, our results suggest that the current policy that requires vegetation clearing before reservoir flooding supports a significant reduction in GHG emissions from these projects and should be improved.

Moreover, climate change and deforestation in the Amazon are factors that may affect atmospheric and surface conditions in the future, which would affect GHG emissions from reservoirs. Studies suggest that one of the impacts from land use change and climate will be changes in Amazon precipitation patterns\textsuperscript{56}. Shifts in the regional climate patterns can influence reservoir emissions by changing the heat balance and surface mixed layer dynamics of hydroelectric reservoirs\textsuperscript{57}. Any changes in precipitation and wind patterns can also affect emissions, as they are important factors to define gas exchange flux variability\textsuperscript{8}. Because of the uncertainty and the lack of knowledge in modeling the correlation between climate patterns and GHG emissions from reservoirs, we are unable to quantify the magnitude of future climate and land use change in our estimates.

The challenge of evaluating net GHG emissions due to reservoir creation is complex because of high spatial and temporal variability and the multiple factors that can interfere in the production, consumption, and emissions of GHGs in tropical reservoirs. The scarcity of data, as well as the gaps in the knowledge about the physical, chemical, and biological processes involved, contribute to the difficulty in estimating the C budget of future reservoirs. Nevertheless, given the large number of hydropower dams that are planned in the Brazilian Amazon region, it is essential to use the available scientific information to develop methods to
evaluate the potential GHG emissions from hydroelectric projects. While the uncertainties of our models are high, the simulations explore a vast range of GHG emission scenarios for each hydropower reservoir and provide information that is useful to support decision-making.
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This chapter is based on research by Felipe A. M. de Faria, Alex Davis, Edson Severini and Paulina Jaramillo that is currently under review in the Proceedings of the National Academy of Sciences

Department of Engineering & Public Policy, Carnegie Mellon University, ‘Heinz College, Carnegie Mellon University

3.1 Introduction

The recent development of large hydropower plants in countries like China and Brazil has stimulated debate about the economic, social, and environmental effects of these projects. Hydropower is regarded as an important electricity generation option because it provides electricity efficiently, reliably, and at a relatively low cost. Additionally, hydropower has the potential to provide important ancillary services to the electric system, as well as non-energy services like flood control and irrigation services. The construction of hydropower plants, like other energy projects, requires substantial investment and employs a significant number of people, with the potential to increase economic activity and tax revenues in surrounding regions - an argument often used to muster support for these projects.

On the other hand, hydropower development has negative socio-economic and environmental impacts. For example, the influx of workers seeking jobs stresses local infrastructure (e.g., hospitals and housing), and can lead to socially undesirable outcomes, such as increases in sexually transmitted diseases, crime, and drug use. The resettlement of those who live in the reservoir areas and the encroachment by outsiders may also lead to deterioration of social cohesion. Moreover, energy projects increase the local demand for services (e.g.,...
road repairs due to heavy truck traffic). Hydropower reservoirs also have negative environmental impacts, as they change the biogeochemical cycles of ecosystems by interrupting the river course, changing the nutrient balance, and shifting oxygen, thermal and sediment flow patterns. Further, the fragmentation of the river ecosystem affects migration of aquatic species, and the flooding of large areas harm local biodiversity.

Despite the important socio-economic impacts of hydropower development, there are few studies examining these issues locally in developing countries. In addition, available studies are limited to qualitative evaluations of just one or two projects. As a result, there are unanswered questions about impacts associated with hydropower. For instance, what happens to county-level economic activity during dam construction and operation? Do socio-economic conditions after the construction of a hydropower plant improve?

Using publicly available data we investigate the relationship between the hydropower development and the socio-economic conditions in Brazilian counties from 1991 to 2010. We find that counties that built hydropower plants had a gross domestic product (GDP) that was, on average, 10% (95% CI: 4% to 16%) greater per year during peak construction than counties with hydropower projects planned but not yet built (control group). After completion of plant construction, that difference diminished, and 14 years after construction starts, the average difference was just 3% (95% CI: -1% to 7%). We find a similar temporary increase for tax revenues. Furthermore, we find little evidence that social indicators (e.g. average income, life expectancy, educational level, access to piped water, access to public electricity, teenage pregnancy levels, and HIV cases) in counties that built hydropower plants differ from those that had plans to build plants that never materialized.
3.2 Data

To explore the socio-economic impacts from hydropower development, we use data from Brazilian counties. Brazil offers a unique setting for this study because of the significant number of counties affected by reservoirs. Currently, the country has 203 large (> 30 Megawatts of installed capacity) hydropower plants in operation, and 10 under construction\textsuperscript{22}. Figure 3-1 shows the spatial distribution of hydropower plants built in Brazil between 1991 and 2010.

Despite the financial incentives available to support hydropower development in Brazil, many areas with hydropower potential do not succeed in developing their hydropower resources. We employ those counties where there were plans to build plants that never materialized as our counterfactual control group. Appendix B (section 7.2) includes a description of the hydropower projects used to define the control group, which are also included in Figure 3-1.
Figure 3-1: Spatial distribution of hydropower plants in Brazil and affected counties. Treated group A represents counties with hydropower plants built between 1991 and 2000. Treated group B represents counties with hydropower plants built between 2000 and 2010. The map presents all counties with undeveloped hydropower projects by 2010, but the control group includes only the counties that are located within a distance of 200 km from the treated counties.

To evaluate the effect of hydropower development on local economies, we gathered population, gross domestic product (GDP), and public revenue data for 5,565 Brazilian counties from 1991 to 2010. We also collected data from electric sector agency, Agência Nacional de Energia Elétrica (ANEEL), to identify the counties that have hydropower plants within their
borders\textsuperscript{37}. Population and GDP data came from the Instituto Brasileiro de Geografia e Estatística\textsuperscript{38}.

While the National Treasure Secretary is the primary source of public budget data in Brazil\textsuperscript{39}, we collected this information from the Instituto de Pesquisa Economica Aplicada (IPEA)\textsuperscript{40}. We used the IPEA database because this institution was the only source providing annual data from 1991 to 1998. Furthermore, IPEA performed a reanalysis of the National Treasure Secretary dataset where the data was adjusted for currency changes, and also standardized according to counties created from 1991 to 2010. Thus, our final budget data includes annual budget information between 1991 and 2010.

Data for human development indicators, for each county, came from the Human Development Brazilian Atlas\textsuperscript{33}. The Atlas database relies on the micro-date from the 1991, 2000, and 2010’s Brazilian censuses. We use 3 indices available in this database (Income, Longevity, and Education) to characterize the socio-economic dimensions of each county. Equations (1), (2) and (3) define the three dependent variables for each county \(i\):

\[
\text{Longevity}_i = \frac{\text{Life expectancy}_i - \text{min(Life expectancy)}}{\text{max(Life expectancy)} - \text{min (Life expectancy)}}
\]

(1)

where life expectancy at birth is measured in years. The minimum and maximum life expectancy values adopted by IPEA are 25 and 85 years old, respectively.

\[
\text{Education}_i = \frac{(A_i + 2B_i + C_i + D_i + E_i)}{4}
\]

(2)

where \(A\) is the percentage of adults (18 and older) with primary education; \(B\) is the percentage of children between 5 and 6 years old in school; \(C\) is the percentage of children between 11 to 13
years in the final years of primary school; D is the percentage of children between 15 and 17 years old who completed primary school; and E is the percentage of young adults between 18 and 20 years old with a high school degree.

\[
Income_i = \frac{\ln (Income per capita_i) - \ln (\text{min reference value})}{\ln (\text{max reference value}) - \ln (\text{min reference value})}
\]  

where \(Income per capita\) is the county’s average income, and the maximum and minimum reference values adopted by IPEA are 4,033 and 8 reais (real values based on August 2010), respectively. Data on access to energy and electricity (% of serviced households) and teenage pregnancy rates (% of women pregnant between 12 and 17 years old) also come from the Atlas. HIV cases came from the health system database: DATASUS\textsuperscript{41}.

### 3.3 Method

The construction of hydropower plants in Brazil is expected to positively affect the counties surrounding hydropower reservoirs. Brazilian environmental law requires the development of an environmental impact assessment (EIA) to evaluate the social and environmental viability of large infrastructure projects, such as hydropower plants. A review of recent Amazon hydroelectric EIAs indicates that there is an expectation that hydro dams will improve economic activity and social welfare in surrounding regions. Hydropower development may increase local economic activity because of the high influx of workers and investments within a short period of time. Furthermore, according to the EIA from recent projects, the long-
term drivers of improved economic conditions are 1) the water resources financial compensation (WRFC), and 2) an increase in tax revenues. The WRFC is a legal mechanism that requires hydro dam owners to pay a fee for the water used to produce electricity. The resources are allocated to counties proportionally according to the share of the reservoir area in each county. Appendix B provides detailed information about the WRFC system.

Local economic activity

In this study we assess the economic effects of hydropower development by comparing counties that built plants between 1991 and 2010 (treated) with counties that had plans to build hydropower but had not yet begun construction by 2010 (controls). Table 3-1 summarizes the characteristics of the treatment and control groups. We focus on two outcomes related to economic activity: GDP and public revenue. Information on annual GDP by sector (agriculture, industry, and services) is available from 1999 to 2010. Annual public revenue information includes the annual public income for a county, which is available from 1991 to 2010. We also break down tax revenue information by its main subaccounts: local services tax (ISS), state transfers (ICMS), and federal government transfers (FPM). Appendix B includes details about the public revenue breakdown.
Table 3-1: County sample statistics (T= treatment and C=controls)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Median</th>
<th>10th percentile</th>
<th>90th percentile</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gross domestic product (1999)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total GDP (x 1000 reais)</td>
<td>T</td>
<td>429</td>
<td>3,562</td>
<td>51</td>
<td>14</td>
<td>402</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>179</td>
<td>544</td>
<td>52</td>
<td>12</td>
<td>329</td>
</tr>
<tr>
<td>Industry GDP (x 1000 reais)</td>
<td>T</td>
<td>64</td>
<td>221</td>
<td>5</td>
<td>1</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>45</td>
<td>198</td>
<td>5</td>
<td>1</td>
<td>52</td>
</tr>
<tr>
<td>Services GDP (x 1000 reais)</td>
<td>T</td>
<td>308</td>
<td>3,121</td>
<td>24</td>
<td>8</td>
<td>196</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>91</td>
<td>275</td>
<td>26</td>
<td>7</td>
<td>135</td>
</tr>
<tr>
<td>Agriculture GDP (x 1000 reais)</td>
<td>T</td>
<td>20</td>
<td>29</td>
<td>10</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>25</td>
<td>36</td>
<td>15</td>
<td>3</td>
<td>52</td>
</tr>
<tr>
<td>Public Revenues (1991)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public Revenue (reais)</td>
<td>T</td>
<td>421</td>
<td>885</td>
<td>168</td>
<td>47</td>
<td>839</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>482</td>
<td>1,338</td>
<td>204</td>
<td>67</td>
<td>788</td>
</tr>
<tr>
<td>Services Tax – ISS (reais)</td>
<td>T</td>
<td>23</td>
<td>74</td>
<td>1</td>
<td>0</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>16</td>
<td>84</td>
<td>1</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>State transfer – ICMS (reais)</td>
<td>T</td>
<td>168</td>
<td>480</td>
<td>48</td>
<td>0</td>
<td>289</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>182</td>
<td>546</td>
<td>63</td>
<td>1</td>
<td>350</td>
</tr>
<tr>
<td>Federal Transfer - FPM (reais)</td>
<td>T</td>
<td>114</td>
<td>113</td>
<td>84</td>
<td>3</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>121</td>
<td>121</td>
<td>93</td>
<td>41</td>
<td>207</td>
</tr>
</tbody>
</table>

We use an event-study approach\textsuperscript{27-30} to examine the relationship between hydropower plant construction and local economic activity. In this approach, counties treated earlier (those who got hydropower earlier in our period of analysis) are compared with counties treated later and with control counties. They are compared before hydropower plants are constructed and after these projects begin operation. By comparing all treated and control counties with themselves across time, we eliminate any time-invariant differences between groups. By comparing counties treated earlier versus later, we eliminate any common factors related to the timing of the event (beginning of construction), assuming the underlying forces leading to hydropower development at any point in time are similar for all treated locations. Finally, by comparing all treated and
control counties with each other, we eliminate any effects that occur over time, assuming these
effects apply to all treated and control counties equally\textsuperscript{27}. Table 3-1 shows that treated and
control groups are similar for some indicators (e.g. agriculture GDP) but differ for others (e.g.
services GDP). To account for those differences, we include control covariates in the regression
models.

Hydropower plant construction happens at different times in different counties. The event
study framework exploits two of the major strengths of our database – the long period of time
and the presence of many counties – in order to obtain a detailed picture of the economic activity
patterns across both time and space\textsuperscript{27}. The event-study technique can control for county-specific
trends in the socio-economic indicators and recover the dynamics of the effect of hydropower
development\textsuperscript{29,30}. Equation (4) describes the mathematical formulation of the econometric model
1:

\begin{equation}
Model1: \text{Economic Indicator}_{it} = \sum_y \beta_y \text{D}_{it}^y + \phi_t + \alpha_i + \gamma_k \text{X}_{k, it} + \epsilon_{it}
\end{equation}

where \text{Economic Indicator}_{it} is the log of GDP (total, industry, services, or agriculture) or public
revenue (total public revenue, ISS, ICMS, and FPM) indicators in county \textit{i} in year \textit{t}. We control
for county fixed effects, \(\alpha_i\), and year fixed effects, \(\phi_t\). We also include a list of control variables
defined by the matrix \(X_k\), which attempts to account for heterogeneous characteristics across
Brazilian counties. \(\gamma_k\) is a vector of the control variables coefficients. First, we include the state
GDP to account for the spatial correlation between counties from the same state. Second, we
include yearly average temperature and precipitation to control for exogenous time-varying
attributes of each county. Third, we include the amount of Itaipu royalties per capita received by
each county. Hydropower plants located in the Parana River basin can receive additional funds from Itaipu (the second largest power plants in the world) because they regulate the downstream water flows to Itaipu allowing the optimization of the energy production. Thus, this variable is required because the royalties are correlated with the dependent variable and event-time dummies. \( e_\text{it} \) is the error term.

The \( D^y_{it} \) are “event-time” dummies that equal one when hydropower construction is \( y \) periods away in a given treated county. Formally, we have:

\[
D^y_{it} = I[t - e_c = y]
\]  

(5)

where \( I[.] \) is an indicator function for the expression in brackets being true, and \( e_c \) is the year that construction of a hydropower plant starts in county \( i \). Therefore, the \( \beta_y \) coefficients in equation (4) represent the time track of the economic indicator relative to the construction starting date, controlling for observed and unobserved heterogeneity. As a result, if hydro dams are randomly assigned to the counties, the restriction \( \beta_y = 0 \) should hold for all \( y < 0 \). In other words, the hydropower plant construction should not be, on average, preceded by trends in the counties’ economic indicators. We normalize \( \beta_{y = 0} = 0 \) because not all the \( \beta_y \) can be identified due to collinearity between the D’s and county fixed effects. Finally, we impose end point restrictions:

\[
\beta_y = \begin{cases} 
\hat{\beta}, & \text{if } y \geq 15 \\
\beta, & \text{if } y \leq -5 
\end{cases}
\]  

(6)
which indicate that any dynamics wear off after 15 years\textsuperscript{29}. This constraint helps to reduce part of the collinearity between the year and event-time dummies. Because the sample is unbalanced in event time, these endpoint coefficients give unequal weight to counties affected by hydropower early or late in the sample\textsuperscript{29}. For this reason, we focus the analysis on the event-time coefficients falling between three years before construction and 14 years after construction, and where the Year 0 is the first year of construction.

The event-study approach relies on the assumption that the characteristics of the counties with plans to develop hydropower projects that do not materialize are similar to those counties that actually had hydropower constructed earlier or later in our period of analysis (random process assumption) conditional on observables. If this assumption is met, we can remove biases associated with siting decisions (e.g., natural advantages\textsuperscript{30,42}, profit maximization\textsuperscript{43}) and the timing of construction (e.g., construction prices and technology advancements). Fortunately, we were able to test and confirm this assumption within this framework by looking at the behavior of the outcome variable prior to hydropower development. If the assumption is reasonable then there should be no observable differences in the event-study coefficients before construction begins, as is the case in our sample. The Results section demonstrates that this assumption is valid for our analysis.

Socio-economic indicators

To evaluate the post-construction impacts from hydropower development on local socio-economic conditions, we employed data for each Brazilian county from the Human Development Brazilian Atlas, a database that contains information about population, household characteristics,
and human development indices based on census information\textsuperscript{33}. We selected three of the major indices from this database to characterize the socio-economic dimensions of each county in 1991, 2000, and 2010. First, the Income Index (\textit{Income}) measures the average purchasing power based on the average income of each county. Second, the Longevity Index (\textit{Longevity}) is a synthesis of living, health, and sanitation conditions, and it relies on life expectancy at birth. The last indicator, Education Index (\textit{Education}), measures the education level of each county through the evaluation of adult education and the progress of young cohorts through the school system. In addition, we examined other indicators that may be affected by hydropower development: the percentage of public access to electricity and piped water, population density, HIV cases, and teenage pregnancy rates.

We applied a differences-in-differences (DD) estimation strategy to estimate the effects of hydropower projects on human development indicators. We used the DD approach because data for the socio-economic indicators is only available every decade (1991, 2000, and 2010). The DD estimation strategy consists of identifying a specific intervention, then comparing the difference in the indices of interest before and after the intervention for the group affected by the treatment with the corresponding difference for the comparison group. In our case, the intervention is the beginning of the operation of hydropower plants. Again, the treatment group consists of counties that got hydropower and the control group consists of counties with plans to build hydropower that didn’t materialize. The DD approach has been widely used for policy evaluation\textsuperscript{34,35}.

We cross-referenced the human development indices with the information organized by ANEEL about the Brazilian hydropower plants, creating a dummy variable (HP) that identifies which and when hydropower plants started operating in each county. We classified the counties
with hydropower reservoirs in two groups. The first group (Group A) contains 46 counties where hydropower operations began in the first period of analysis (1991-2000). The second group (Group B) contains 101 counties that started operations during the second period (2000-2010). As multiple plants affect some counties, we restricted the analysis for groups A and B for the counties that were not receiving WRFC funds from plants built before 1991. The treatment parameter is the year that the power plant starts generating electricity, so we are not including a specific assessment of the construction stage.

Equation (7) defines the basic DD specification:

\[ Model 2 - HumanDevelopmentIndex_{it} = \psi_1 (HP_t \times T_t) + T_t + HP_t + \alpha_t + \beta_k Z_{k,lt} + \epsilon_{it} \]  

The dependent variable listed in equation (7) (Human Development Index) represents the indices selected for analysis, which include income, longevity, education, access to electricity and piped water, teenage pregnancy rates, and HIV cases. T is a dummy variable that identifies the post-construction period and controls for timing effects. We also separated the analysis in two periods: short term versus long term. The short term is the period between 1991 and 2000 for group A, and 2000 to 2010 for Group B (T=1 if year equals 2000 for group A, and 2010 for group B, respectively). The long term period is 1991 to 2010 (T=1 if year equals 2010, with 2000 values excluded), and is observed only for group A. HP is a dummy variable for each treated group (Group A and Group B) and controls for the time-invariant differences between control and treated counties. The interaction between HP and T defines the variable of interest, which evaluates the effect of the hydropower plant on socio-economic indicators. The \( Z_k \) matrix contains a list of control variables that include annual temperature and precipitation, and \( \beta_k \) is the
vector of regression coefficients from those control variables. We applied the same model to estimate the impact on the log of population density as well.

County Creation Issue

Between 1991 and 2010, more than a thousand new counties were created in Brazil. This generates a problem for our analysis as the observation unit (county) changed over time. To overcome this issue, we mapped the changes between 1991 and 2010 and created an identifier to match new counties to their original territory. Then, we merged the new territories to their original one and applied the 1991 baseline county as our observation unit. We aggregated the variables of interest accordingly. This procedure leads to an additional problem because now we can have treated and not treated counties in the same territory. To deal with this additional problem, we weight the event-study and DD treatment dummy variables using the 2010 counties’ territory as the weight. For example, if 60% of the territory of a county in 1991 becomes a separate 2010 county (where hydropower development took place), while the remaining 40% of the 1991 area became a non-treated county in 2010, the dummy variable value for the new treated county will be assumed to be 0.6.

Control Group

Despite the financial incentives available to support hydropower development in Brazil, many areas with hydropower potential do not succeed in developing their hydropower resources.
We employed those counties as our counterfactual control group. The reasons why some hydropower projects are still undeveloped include: lack of financial viability, environmental and social restrictions, and legal or regulatory issues. We include this constraint to control for biases associated with natural advantages\textsuperscript{30,42}, and siting decisions\textsuperscript{43}. To identify those counties, we cross-referenced the counties’ map with a database\textsuperscript{44} provided by ANEEL that contains the precise location of hydropower plant sites studied and approved by the agency. This database has information about the projects’ characteristics and their development stages (master plan, viability, basic design, under construction, operation). We selected the counties at stages before construction as our control group. Additionally, we constrained the control group by using only counties within 200km from our treated counties, resulting in a total of 111 counties.

3.4 Results and Discussion

3.4.1 Hydropower development and local economic activity

Figure 3-2 presents the results of the event-study analysis for the total GDP and its subcategories (industry, services, and agriculture). In order to test the validity of the event-study approach, we look at the behavior of the outcome variable prior to hydropower development. The coefficients represent the time path\textsuperscript{29} of the GDP relative to the date when construction of a hydropower plant started. Except for one coefficient in agricultural GDP, there were no observable differences between treated and control groups before construction began, supporting the critical assumption that control and treated counties were on similar economic paths before hydropower development.
Figure 3-2 also shows that, during the construction period, treated counties had a greater average increase in total GDP than control counties. This growth is insignificant during the first two years, but achieves a peak in the third year after construction begins, when the average annual GDP growth is 10% (95% CI: 1% to 20%) larger than control counties. After this peak, such GDP difference substantially decreases, although it does not fully return to pre-construction levels. During the construction and operational stages, the average effect of hydropower on the local GDP is 4% (95% CI: -2% to 10%) and 5% (95% CI: 0% to 10%), respectively.

Figure 3-2: Gross domestic product (GDP) event-study regression results. Titles refer to dependent variables. The y-axis represents the coefficient estimates ($b_y$s from Model 1 defined in the Method section) for each gross domestic product indicator in log points. To obtain the results in percentage increase relative to the pre-construction period compute $\exp(\text{Estimate}-1)$. The x-axis describes the coefficient outcome in each year relative to the first construction year (Year 0). The light orange boxes represent the average period of hydropower plant construction from our database (approximately 4 years). Points represent the average effect and bars represents the 95% confidence intervals defined as two times the standard errors (robust standard errors are clustered at the county level and hydropower plant).
Figure 3-2 shows that the increase in GDP is likely due to an increase in industrial GDP, which increases very fast a few years after the beginning of construction. At the peak (4th year), hydropower development is associated with an industrial GDP increase of 39% (95% CI: 7% to 80%) per year compared to the pre-construction phase. However, 14 years after the start of construction this effect drops to an average of 9% (95% CI: -3% to 24%). A similar trend is observed in the services sector, where there is an increase of 7% (95% CI: 1% to 15%) in the third year with a gradual reduction thereafter.

In contrast, hydropower development is associated with a loss in agricultural GDP. In the sixth year after construction begins, there is a 10% reduction (95% CI: -3% to -18%) in agricultural GDP. This outcome is likely the result of two main factors. First, the flooding that occurs to create the reservoirs reduces the available land for agricultural production, and possibly affects fishing resources\textsuperscript{13}. Second, new opportunities in the services and industrial sectors likely deprive the agricultural sector from workers.

Using the same event-study approach, we assess the relationship between hydropower development and public revenues. Figure 3-3 shows that public revenues increase an average of 6% (95% CI: 0% to 10%) after the beginning of construction. Public revenues continue to rise when operations start, achieving a peak (15%; 95% CI: 9% to 21%) eight years after construction begins. The first increase in public revenue is associated with the growth in the ISS (local tax). ISS revenues more than double during the construction period but their positive effects are limited to 11 years after construction begins.

ICMS revenues (state transfers) lead the second increase in the public revenue. This result is unsurprising given that the proportion of the ICMS received by each county varies by state, but is a function of the value each county adds to the overall state economy. As the treated
counties’ GDP increase due to the construction and operation of the power plants, the ICMS transfers to those counties also grow. The increasing part of the curve for ICMS is associated with additional electricity generation (and consumption) in the first years of operation. However, the ICMS return to pre-construction levels after the eighth year may be the result of continued growth in the rest of the state once construction is completed. This is the case if electricity generated in the hydropower plants is consumed in other parts of the state, and GDP in those places grows faster. Therefore, the relative contribution of the hydropower plant (and the county where it is located) to the overall state economy decreases with time, leading to a decrease in the ICMS transfers to the affected county.

Finally, our analysis indicates a long-run negative trend on FPM (federal transfers) to the county’s budgets. The FPM distribution relies on complex criteria that include the size of the population and the state where the county is located. FPM transfers can decrease for a given county if the share of federal resources to other counties in the state increases in relation to total amount of resources available\(^\text{31}\).
Figure 3-3: Public revenue event-study regression results. Titles refer to dependent variables. The y-axis represents the coefficient estimates ($b_i$'s from Model 1 defined in the Method section) for each revenue indicator in log points. The x-axis describes the coefficient outcome as function of the years from beginning of the construction (Year 0). The light orange boxes represent the average period of construction the hydropower plants from our database (approximately 4 years). Points represent the average effect and error bars represent the 95% confidence intervals defined as two times the standard errors (robust standard errors are clustered at the county level and hydropower plant level).

Sensitivity and Heterogeneity

We assessed the sensitivity of our models to alternative specifications, including regressions without control variables, and using alternative control groups (see Appendix B). The removal of covariates did not affect the coefficients but increased the standard errors, suggesting that the control covariates help to explain part of the noise from our data. Furthermore, if we used all Brazilian counties that did not build hydropower plants as controls in our analysis, the effects of hydropower development are greater for GDP but lower for taxes, indicating that failing to control for natural advantages and siting decisions slightly biases the results. Appendix B (section 7.5) also includes assumption checks (e.g. the strict exogeneity assumption) and a
residual analysis. These additional model tests and sensitivity analysis qualitatively support our main findings.

We also evaluated the heterogeneity of hydropower development impacts by dividing the data in four criteria: 1) larger (greater than 500 MW) versus smaller plants (between 30 and 500 MW); 2) utility versus industrial ownership; 3) small (less than 30,000 people) versus large (greater than 30,000 people) counties, and 4) more developed (those with human development index greater than 0.4 in 1991) versus less developed counties (human development index less than 0.4). Most strikingly, we find that smaller hydropower plants perform better in terms of GDP and tax revenues than larger plants. Figure 3-4 describes the first potential reason: smaller plants did not negatively affect the agricultural sector (as they often required less flooded area) while larger plants were associated with substantial reductions in agricultural production. Second, ICMS revenues are greater for smaller power plants because they generate electricity that may be used locally, leading to increased ICMS revenues (See Figure S3, Appendix B, section 7.6.1.). Larger plants, in contrast, are often connected through interstate high voltage transmission lines to the load areas, increasing tax revenues in the state where the electricity is consumed. Therefore, the tax structure is a relevant driver to define the economic benefits allocation between hydropower producing regions and places with high electricity demand.

Our analysis suggests that counties where industry facilities and hydropower were simultaneously constructed have greater tax and GDP revenues than those without such involvement from the industry (See Figures S4 and S5, Appendix B, section 7.6.1). Industry-owned projects are likely developed to supply electricity to industries like mining and aluminum manufacturing, which contribute to industrial GDP. Those electro-intensive industries build power plants close to their facilities to ensure a steady supply of electricity. Finally, our results
suggest that small counties were significantly affected by hydropower development while larger counties are barely affected (See Figures S6 and S7, Appendix B). We don’t find a clear distinction between hydropower effects on more or less developed counties (See Figures S8 and S9, Appendix B). Appendix B (section 7.6.1) contains the detailed results and discussion about heterogeneity.
Figure 3-4: Smaller (< 500 MW of installed capacity) versus Larger hydropower plants (> 500 MW of installed capacity): gross domestic product event-study regression results. Titles refer to dependent variables. The y-axis represents the coefficient estimates ($b_y$'s from Model 1 defined in the Method section) for each gross domestic product indicator in log points. To obtain the results in percentage increase relative to the pre-construction period compute $\exp(Estimate-1)$. The x-axis describes the coefficient outcome in each year relative to the first construction year (Year 0). The light orange boxes represent the average period of hydropower plant construction from our database (approximately 4 years). Points represent the average effect and bars represents the 95% confidence intervals defined as two times the standard errors (robust standard errors are clustered at the county level and hydropower plant).
3.4.2 Hydropower development and socio-economic indicators

Figure 3-5 depicts the estimated coefficients for our three human development indicators as well as the other variables of interest. The regression results indicate that the socioeconomic indicators for counties that built hydropower plants were not significantly different (either in the short or long run) from counties in the control group. As in previous studies, we do not observe population agglomeration\textsuperscript{30}. For education, access to piped water and electricity, and teenager pregnancy we cannot determine whether the relationship was negative or positive. The absence of long-term effects over the local economy likely explains the lack of positive social impacts.

Our results also suggest that the WRFC policy has been not effective in improving conditions relative to the control group that did not receive such payments. Appendix B (section 7.6.2) includes an additional analysis where we assess the socio-economic impacts of the WRFC policy alone. Specifically, we evaluate 379 counties affected by hydropower plants in operation before 1991 that started receiving WRFC funds only in 1991, when the compensation policy was put into effect. The WRFC implementation represents a discontinuity for the treatment group and allows us to investigate the effect of the WRFC alone, excluding the construction effect. We find that WRFC policy is associated with relative deterioration of socio-economic indicators (e.g., income and life expectancy) in the long run (See Figure S10, Appendix B).
Figure 3-5: Difference-in-differences regression results for the human development indicators and other outcomes of interest for A and B treatment groups (described in the Methods section). Bars represent the average $\gamma_i$ coefficient estimates from equation (7) described in the Methods section. Error bars represent the 95% confidence intervals defined as two times the standard errors (robust standard errors are clustered at the county level and hydropower plant level). Short term represents the first decade after hydropower development (A: 1991-2000 and B: 2000-2010). Long term represents two decades after hydropower development (Only A: 1991-2010).
3.5 Policy implications

In this chapter we have provided evidence that the positive effects of hydropower projects on local economies in Brazil are the result of two cycles: construction and operation. We found, however, that most of those effects are short-lived, and disappear in less than 15 years. This is particularly important because large hydropower dams (and their environmental consequences) last many decades or even centuries. Additionally, we did not find evidence that hydropower development contributes to long-term improvements for local social indicators. Hence, the empirical evidence does not support long-term positive economic and social impacts described in the environmental impact assessments for Brazilian projects. Our results highlight the need for empirically driven methods to assess the socio-economic viability of hydropower development in Brazil. We acknowledge, however, that this study focuses only on the local effects and does not evaluate the overall effects of the electricity transmitted to other parts of the Brazilian economy, which may in fact be more positive that our local results suggest.

This work also brings new empirical evidence to the debate about financial incentives for infrastructure and energy projects. Often, state and local governments use tax exemptions, subsidies, and changes in tax structure to try to attract industry and thus promote regional growth. The quick reversion of local economic activity to pre-construction levels in Brazilian counties affected by hydropower plants relative to control counties reveals the lack of local agglomeration spillovers, and suggests that policies aimed at spurring hydropower development to support local well-being may not be effective.
References

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4. COMPARING ALTERNATIVES TO HYDROPOWER DEVELOPMENT IN THE AMAZON

This chapter is based on research by Felipe A. M. de Faria and Paulina Jaramillo currently in preparation for submission to Nature Energy

Department of Engineering & Public Policy, Carnegie Mellon University.

4.1 Introduction

Since the middle of the 20th century, Brazil has been supplying most of its growing electricity demand by building large hydropower plants. Currently, hydropower plants larger than 30 MW comprise 61% of the total installed capacity (144 GW). Recently, the construction of new hydropower plants has been concentrated in the Amazon basin, where large plants like Jirau (3,750 MW), Santo Antônio (3,150 MW), and Belo Monte (11,200 MW) were recently built. The Amazon region is the focus of the recent hydropower development given that most of the hydropower capacity in other regions has already been constructed. In addition to the previously listed projects, there are several projects currently under construction, such as Teles Pires (1,820 MW), São Manoel (746 MW) and Sinop (461 MW). Moreover, the latest government energy plan indicates that most of the new power plants will continue to be built over the Amazonian forest with São Luis do Tapajos (6,133 MW) and São Simão Alto (3,509 MW) as notable examples.

Although hydropower has been seen as the main supply source to meet the growing demand for electricity, projects located in the Amazon could have significant environmental and social impacts. The reservoirs in these power plants replace river and land, flooding
agricultural land, flora, and fauna. The dams also block the natural river flow affecting the migration of aquatic species and resulting in changes in the oxygen, thermal, and sediment conditions in the reservoir area and downstream. In some cases, the flooding and decay of large stocks of biomass in the reservoir area lead to greenhouse gas emissions with magnitude comparable to fossil fuel power plants. Furthermore, large hydropower projects also affect the local population through the resettlement of people living in the reservoir areas and the deterioration of social cohesion because of the high influx of workers, and loss of Agricultural GDP.

In order to better understand the potential tradeoffs associated with hydropower development in the Amazon, it is essential to develop methods and indicators to compare the costs and benefits of these power plants against other alternatives for power generation. In this study, we develop different capacity expansion scenarios for the Brazilian power system. We simulate the electric system operations in order to estimate performance indicators such as land use, electricity production and operational costs, quantity of stored energy in the reservoirs, level of wind curtailment, and greenhouse gas (GHG) emissions across the different scenarios. The alternative scenarios include replacing the Amazonian hydropower capacity with wind power in the northeast and south regions, or natural gas plants in the southeast.

The results of this modeling effort suggest that higher wind penetration will reduce land use requirements for electricity generation and increase the average capacity of the system to store water in hydropower reservoirs because of the negative correlation between the peaks and valleys of hydro and wind power generation through the year. However, when wind penetration reaches 24% to 28% of total system capacity, generation from thermal power plants increase, leading to higher operational costs and GHG emissions than the baseline, hydro-based scenario.
Moreover, we also assessed the impact on costs and GHG emissions of replacing the more polluting coal, diesel, and oil power plants by less polluting natural gas power plants. Finally, we assess the impact of replacing Amazon hydropower with natural gas power plants, which increases the costs and GHG emissions of energy development compared to the baseline. Our results indicate that a combination of an expansion of renewable resources and natural gas power plants is likely a more effective strategy to replace Amazonia hydropower while reducing emissions from the Brazilian electric system.

4.2 Data

4.2.1 Brazil’s integrated electric system

As of May 2016, Brazil has 143 GW of installed power generation capacity comprising 204 large hydropower plants (87 GW), 2,888 thermal power plants (40 GW), 2 nuclear power plants (2 GW), 356 wind parks (9 GW), and 456 small hydropower plants with less than 30 MW (5 GW)\(^1\). A national system operator (Operador Nacional do Sistema - ONS) is responsible for the operations of the integrated power system and controls the dispatch of power plants to instantaneously match supply and demand for electricity, while minimizing operation costs.

Modelling the optimal operation of a complex and integrated hydrothermal power network like the Brazilian electric system requires extensive and detailed data about each power plant, transmission lines, and loads. The Empresa de Pesquisa Energetica (EPE) is the Brazilian state company responsible for creating the long-term energy plans for the country. Every year, EPE issues an expansion plan (Plano Decenal de Energia) that includes a set of files containing
the detailed characteristics of each power plant used to model the hydrothermal operation of the future system\textsuperscript{16}. Table 4-1 includes the major characteristics that are available about each power plant from the EPE report released in January 2015 (hereafter the 2015 EPE report files), which focused on modelling the system from 2013 to 2023 but provided data up to 2028. We used 2015 EPE report files as the reference scenario (baseline) to represent the electricity generation capacity expansion from 2013 to 2028.

Table 4-1: Major information about the Brazilian electric system available in the EPE database

<table>
<thead>
<tr>
<th>Major variables</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydropower plants</strong></td>
<td></td>
</tr>
<tr>
<td>Operating Data</td>
<td></td>
</tr>
<tr>
<td>Minimum flow (m\textsuperscript{3}/s)</td>
<td>Represents the minimum outflow of the plant, which may be required because of technical constraints.</td>
</tr>
<tr>
<td>Maximum flow (m\textsuperscript{3}/s)</td>
<td>Represents the maximum outflow through the turbines.</td>
</tr>
<tr>
<td>Minimum total outflow (m\textsuperscript{3}/s)</td>
<td>Represents a lower bound on the sum of turbined and spilled outflows, required for example to assure navigation along the river.</td>
</tr>
<tr>
<td>Production coefficient (MW/m\textsuperscript{3}/s)</td>
<td>Represents the average production coefficient in the plant</td>
</tr>
<tr>
<td>Installed capacity (MW)</td>
<td>Maximum limit of the plant power production.</td>
</tr>
<tr>
<td>Number of generators</td>
<td>Number of generating units in the power plant</td>
</tr>
<tr>
<td>Forced outage rate</td>
<td>Represents the effect of random equipment outages on the hydro plant production capacity.</td>
</tr>
<tr>
<td>Composite outage rate</td>
<td>Represents the joint effect of equipment maintenance and equipment outage on the hydro plant production capacity.</td>
</tr>
<tr>
<td>Characteristics of the downstream reservoirs</td>
<td>Indicate the characteristics of the cascade structure</td>
</tr>
<tr>
<td>Plant parameters</td>
<td></td>
</tr>
<tr>
<td>Minimum/maximum reservoir storage (hm\textsuperscript{3})</td>
<td>Minimum and maximum reservoir storage capacities</td>
</tr>
<tr>
<td>Spillway type</td>
<td>Indicate if the plant can spill at any reservoir storage level.</td>
</tr>
<tr>
<td>Storage (hm\textsuperscript{3})</td>
<td>Constant water volume of the run-of-the-river plant</td>
</tr>
<tr>
<td>Area (km\textsuperscript{2})</td>
<td>Reservoir area</td>
</tr>
<tr>
<td>Production coefficient × storage</td>
<td>Represents the effect of head variation with storage.</td>
</tr>
<tr>
<td><strong>Thermal plants</strong></td>
<td></td>
</tr>
<tr>
<td>Operating Data</td>
<td></td>
</tr>
<tr>
<td>Fuel characteristics</td>
<td>Information about source, unit (ton, m\textsuperscript{3}, gallon, etc.) and price ($/unit)</td>
</tr>
<tr>
<td>Minimum generation (MW)</td>
<td>Minimum limit of the plant power output.</td>
</tr>
<tr>
<td>Maximum generation (MW)</td>
<td>Maximum limit of the plant power output.</td>
</tr>
<tr>
<td>Forced outage rate – FOR (%)</td>
<td>Represents the effect of random equipment outages on the thermal plant production capacity.</td>
</tr>
<tr>
<td>Composite outage rate – COR (%)</td>
<td>Represents the joint effect of equipment maintenance and equipment outage on the thermal plant production capacity.</td>
</tr>
<tr>
<td>Plant type</td>
<td>Standard or &quot;must-run&quot;</td>
</tr>
<tr>
<td><strong>Loads by subsystem</strong></td>
<td>The monthly load variability is represented by three load blocks (see method)</td>
</tr>
<tr>
<td><strong>Subsystem interconnection</strong></td>
<td>Information about the interconnection between subsystems</td>
</tr>
</tbody>
</table>
EPE models the Brazilian system by dividing it in 10 subsystems: 1) North, 2) Northeast, 3) Southeast, 4) South, 5) Paraná, 6) Itaipu, 7) Teles Pires and Tapajós, 8) Belo Monte, 9) Acre and Roraima, and 10) Manaus, Amapá and Boa Vista. Some of these subsystems contain power plants and loads (e.g. Southeast), but others contain just generation (e.g. Belo Monte). Figure 4-1 describes a scheme of the subsystems and their interconnection.
Figure 4-1: Brazilian integrated system scheme (forecasted capacity by 2028). Red figures inside the boxes represent the “other renewables” average power (wind, solar, biomass). Source: adapted from EPE, 2014.
4.2.2 Representation of the current system

The EPE’s 2015 energy report database contains data for the Brazilian interconnected electric system as of May 2013 and contains 133 hydroelectric power plants (86 GW) and 99 thermal power plants (20 GW). Table S1 and S2 in the Appendix C (section 8.2) contain the main characteristics of the hydroelectric and thermal power plants represented in the current system, respectively. Other renewables like wind, biomass, solar, and small hydro account for less than 10 GW and their energy output are modelled as a group that includes all power plants by subsystem. Appendix C provides more details about the EPE’s modelling assumptions about the wind, biomass, solar and small hydropower plants.

4.2.3 Baseline scenario

To supply growing demand for electricity, EPE defines a set of hydroelectric and thermal projects that should start operations by 2028 (database horizon). Each project listed has a unique operating start date such that the power plants in the database are under different development stages throughout the period of analysis (see the complete schedule in Appendix C). As a result, some power plants in the database are already in operation, under construction or in an advanced licensing stage, while others are just in the proposal stage and may ultimately remain undeveloped. For purposes of this analysis, we assume all these plants will be operational in our baseline scenario.

According to the EPE expansion plan, Brazil will need to build approximately 55 GW of new hydropower plants, 20 GW of thermal plants, and 26 GW of wind plants to meet electricity demand by 2028. Therefore, most of the new capacity will continue to come from hydropower
plants. Hydropower plants located in the Amazon are expected to account for 46 out of 55 GW of the new hydropower capacity described in the EPE’s plan (Table 4-2).

**Table 4-2: Recent or planned large hydropower plants in the Amazon (2013 - 2028)**

<table>
<thead>
<tr>
<th>Name</th>
<th>Installed Capacity (MW)</th>
<th>Lat.</th>
<th>Long.</th>
<th>Reservoir Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belo Monte</td>
<td>11,233</td>
<td>-3.1</td>
<td>-51.8</td>
<td>440</td>
</tr>
<tr>
<td>Bem Querer</td>
<td>708</td>
<td>1.9</td>
<td>-61.0</td>
<td>559</td>
</tr>
<tr>
<td>Cachoeira do Caldeirão</td>
<td>219</td>
<td>0.9</td>
<td>-51.3</td>
<td>51</td>
</tr>
<tr>
<td>Cachoeira do Cai</td>
<td>802</td>
<td>-5.1</td>
<td>-56.5</td>
<td>420</td>
</tr>
<tr>
<td>Cachoeira dos Patos</td>
<td>528</td>
<td>-5.9</td>
<td>-55.8</td>
<td>117</td>
</tr>
<tr>
<td>Carecuru</td>
<td>240</td>
<td>-0.1</td>
<td>-53.0</td>
<td>184</td>
</tr>
<tr>
<td>Colíder</td>
<td>300</td>
<td>-11.0</td>
<td>-55.8</td>
<td>123</td>
</tr>
<tr>
<td>Ferreira Gomes</td>
<td>252</td>
<td>0.9</td>
<td>-51.2</td>
<td>12</td>
</tr>
<tr>
<td>Jamanxim</td>
<td>881</td>
<td>-5.6</td>
<td>-55.9</td>
<td>74</td>
</tr>
<tr>
<td>Jardim de Ouro</td>
<td>227</td>
<td>-6.3</td>
<td>-55.8</td>
<td>426</td>
</tr>
<tr>
<td>Jatobá</td>
<td>2,338</td>
<td>-5.2</td>
<td>-56.9</td>
<td>646</td>
</tr>
<tr>
<td>Jirau</td>
<td>3,750</td>
<td>-9.3</td>
<td>-64.7</td>
<td>303</td>
</tr>
<tr>
<td>Marabá</td>
<td>1,708</td>
<td>-5.3</td>
<td>-49.1</td>
<td>1,115</td>
</tr>
<tr>
<td>Paradão A</td>
<td>199</td>
<td>2.9</td>
<td>-61.6</td>
<td>17</td>
</tr>
<tr>
<td>São Luís do Tapajós</td>
<td>8,040</td>
<td>-4.6</td>
<td>-56.8</td>
<td>722</td>
</tr>
<tr>
<td>Serra Quebrada</td>
<td>1,328</td>
<td>-5.7</td>
<td>-47.5</td>
<td>386</td>
</tr>
<tr>
<td>São Simão Alto</td>
<td>3,509</td>
<td>-8.2</td>
<td>-58.3</td>
<td>284</td>
</tr>
<tr>
<td>Santa Isabel</td>
<td>1,087</td>
<td>-6.1</td>
<td>-48.3</td>
<td>1,850</td>
</tr>
<tr>
<td>São Manoel</td>
<td>700</td>
<td>-9.2</td>
<td>-57.1</td>
<td>53</td>
</tr>
<tr>
<td>Sinop</td>
<td>400</td>
<td>-11.3</td>
<td>-55.5</td>
<td>330</td>
</tr>
<tr>
<td>Salto Augusto de Baixo</td>
<td>1,461</td>
<td>-8.9</td>
<td>-58.6</td>
<td>125</td>
</tr>
<tr>
<td>Santo Antônio do Jari</td>
<td>370</td>
<td>-0.7</td>
<td>-52.5</td>
<td>32</td>
</tr>
<tr>
<td>Santo Antônio</td>
<td>3,151</td>
<td>-8.8</td>
<td>-63.9</td>
<td>271</td>
</tr>
<tr>
<td>Tabajara</td>
<td>350</td>
<td>-8.9</td>
<td>-62.2</td>
<td>129</td>
</tr>
<tr>
<td>Teles Pires</td>
<td>1,820</td>
<td>-9.3</td>
<td>-56.8</td>
<td>123</td>
</tr>
<tr>
<td>Tucumã</td>
<td>453</td>
<td>-10.5</td>
<td>-58.4</td>
<td>219</td>
</tr>
</tbody>
</table>

**Total**          | **46,055**             |      |       | **9,012**            |
4.2.4 Introducing wind generation in the model

The baseline scenario forecasts the need for additional 26 GW of wind capacity by 2028. Brazilian wind resources are concentrated in the Northeast and South subsystems. Wind energy production variability introduces complexity to the system operation; however, this complexity is not represented by the current information provided by EPE. The EPE’s database treats the renewable sources (excluding large hydropower plants) like groups of projects in each subsystem. The renewable sources are also assumed to be must-run plants with a constant monthly electricity output (Figure S2 in the Appendix C). Thus, the EPE’s modelling approach accounts only for an average seasonal variability, but does not account for the stochastic nature of the wind speeds and the daily variability of wind output.

To overcome this issue, we created wind generation series using wind speed data from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR)\(^{17}\) for the current and future wind parks. NCEP-CFSR is an atmospheric reanalysis product available at an hourly time resolution from 1979 to the present and a horizontal resolution of \(0.5^\circ\) latitude \(\times\) \(0.5^\circ\) longitude. Reanalysis data are attractive for wind-power studies because they can offer wind speed data for large areas and long time periods and in locations where historical data are not available\(^{18}\). To define the position of the current and future wind parks we used data from the Brazilian electricity agency ANEEL that provides the geographical position of each wind park in operation and under earlier development stages\(^{19}\) (See Table S3 and Figure S3 in the Appendix C). We evaluated the validity of using CSFR wind speeds to generate wind power output series using real data from 32 wind parks in Brazil. The appendix for this chapter details this validation analysis (Appendix C, section 8.4).
4.2.5 Power plant investment costs

The Chamber of Electric Energy Trading (Câmara de Comercialização de Energia Elétrica - CCEE, in Portuguese), which is the Brazilian electricity market operator, provides a dataset of all new power plants that sold energy in public auction since 2005\textsuperscript{20}. This database contains the installed capacity and the forecasted capital costs for 826 power plants built from 2005 to 2015. We applied the CCEE cost information to estimate the total construction costs of the future power plants. Appendix C (section 8.5) contains a detailed description about the CCEE data.

4.3 Method

4.3.1. Power systems model

We imported 2015 EPE report files to model current and future power plants using SDDP (stochastic dual dynamic programming), which is a hydrothermal dispatch model with the representation of the transmission network. The model calculates the least-cost stochastic operating policy of the electric system, taking into account operational details of the plants, such as water inflows and operational limits, and the stochastic behaviour of the system caused by renewable variability\textsuperscript{21-23}.

In purely thermal systems, the operation cost of each plant depends essentially on its fuel cost - the plants with the lower fuel costs are dispatched first. However, the operation of hydrothermal systems is more complex because the system operator needs to decide every time whether to save or use water from the reservoirs. If the operator decides to use hydro energy today, and future inflows are high, allowing for reservoir storage recovery, the system operation
will be efficient\textsuperscript{23}. In contrast, if a drought occurs, it may be necessary to use more expensive thermal generation in the future, or even interrupt the supply. Similarly, if storage levels are kept high through more use of thermal today, and high inflows occur in the future, reservoirs may spill, which results in a waste of energy and higher operational costs. If a drought occurs instead, storage displaces thermal generation and the operation is efficient\textsuperscript{23}. The problem is stochastic because water inflow to the reservoirs is a result of a random process and it is impossible to have a perfect forecast of future inflows\textsuperscript{22}. Additionally, most inflow sequences are serially correlated affecting the operation decisions\textsuperscript{23}. In other words, if the inflow of the past month was wetter than the average, there is a tendency that the inflows in the next few months will be wetter too.

The SDDP application in this study allows the comparison of different expansion plans taking into account the hydrothermal scheduling issue. SDDP determines the sequence of hydro releases, which minimizes the expected thermal operation costs (given by fuel costs and penalties for rationing) during the planning horizon\textsuperscript{21,23}. Renewable sources, like wind, are treated as a negative load with zero cost. The SDDP algorithm decomposes the multi-stage stochastic problem into several one-stage sub-problems. Each sub-problem corresponds to a linearized optimal power flow with additional constraints representing the hydro reservoir equations and a piecewise linear approximation of the expected future cost function\textsuperscript{21,22}. For a given stage of the problem, the future cost is a function of the reservoir storage levels and inflows. SDDP incorporates inflow stochastic characteristic by solving the optimization problem several times (Monte Carlo simulation). We solve the optimization for each scenario using 400 simulations. The algorithm also incorporates serial autocorrelation of inflows by modeling the water inflows to the reservoirs using an autoregressive linear regression model based on the historical monthly
inflows for each hydropower reservoir. Appendix C (section 8.3) contains more details about hydrothermal scheduling issue and the SDDP algorithm.

Moreover, a fair comparison between different expansion plans should take into account that each scenario should provide similar levels of system reliability. We built our alternative scenarios to provide system reliability levels comparable to the baseline. We measured the system reliability using the lost load probability over the planning horizon. Finally, we compared the baseline against the alternative expansion plans using environmental (e.g. land use and greenhouse gas emissions), system operation (e.g. level of stored energy in the hydroelectric reservoirs and wind curtailment) and cost (e.g. investment and operational costs) indicators.

4.3.2. Demand and interconnection representation

The EPE database represents electricity demand in a typical day in the Brazilian system using three load blocks within each month (stage): high, medium and low. EPE projects future electricity demand based on demographic, economic, and sectorial studies about residential and industrial electricity consumption\textsuperscript{24}. The loads are grouped by subsystem\textsuperscript{16} and in a typical day, the high load happens between 6 pm and 9 pm; the low load occurs from 0 am to 7 am; and the rest of hours of the day are considered medium load\textsuperscript{25}. Therefore, three pairs of duration (hours) and demand (GWh) by month represent each load block. Given this information, we optimize system operations to meet the demand in monthly time steps where three different load levels (blocks) represent the daily load variability within each month. All scenarios have the same demand profile. Figure 4-2 shows the annual load duration curves for 2014 and 2028. Finally, we represent the interconnection between subsystems as described in Figure 4-1, but we relax the transmission capacity constraints assuming no restriction between the sub-systems.
Figure 4-2: Load duration curves for 2014 and 2028. Load duration curve is a graphical representation of the association between generating capacity requirements and capacity utilization.

4.3.3. Alternative scenarios

The objective of this chapter is to compare different electricity generation expansion scenarios for the Brazilian integrated electric system using performance indicators that characterize the technical, economic, and environmental features of each scenario. The baseline
scenario was created using government plans and relies heavily on large hydropower plants in the Amazon. According to the EPE plan, in 2028, wind power corresponds to only 15% of the total installed capacity. In addition, we developed four alternatives scenarios:

1. Scenario “Wind27”: Replaces hydroelectric power plants scheduled for operation in the Amazon after 2020 with wind parks so that by 2028 wind power accounts for 27% of total installed capacity.
2. Scenario “Wind39”: Replaces hydroelectric power plants scheduled for operation in the Amazon after 2013 with wind parks so that by 2028 wind power accounts for 39% of the total installed capacity.
3. Scenario “Natural Gas”: Replaces hydroelectric power plants scheduled for operation in the Amazon after 2020 with natural gas power plants
4. Scenario “Coal/Oil/Diesel Retirement”: Assumes the same conditions detailed in the “Wind39” scenario, but, additionally, all current and future coal, oil and diesel power plants are retired and replaced by natural gas power plants with the same capacity.

To estimate the installed capacity of wind parks needed in the “Wind 27” and “Wind39” scenarios that replace the hydropower in the baseline scenario, we did a first order approximation by multiplying the installed capacity of the new hydropower plants by 0.55 (average hydro capacity factor) and then dividing the result by 0.4 (average capacity factor for wind in Brazil). This approximation overestimated the installed capacity creating excessive wind curtailment in the SDDP simulations. Thus, we adjusted the wind expansion scenarios by reducing wind power capacity parametrically while maintaining similar levels of lost load across the alternative
scenarios and the baseline. We followed an equivalent procedure to estimate natural gas capacity in the last scenario, but we multiplied the hydropower capacity in the schedule by 0.6.

We represented the new wind installed capacity in the model by creating groups of 25 fictitious wind parks of 30 MW of installed capacity each. Thus, each group has 750 MW of installed capacity. In order to define the location of each wind park in the group, we applied a lottery with replacement. This lottery is based on a sample of 1,065 wind parks that are under early licensing stage and located in the Northeast and South states (see Figure S3 in the Appendix C). We then created wind energy generation series for each group of wind parks (750 MW) by simulating the energy output from each fictitious power plant individually using the NCEP-CSFR hourly wind speeds during 32 years (1979 -2010). Next, we aggregated the results for the 25 wind parks within each group by month and load block. As a result, each group of 750 MW wind parks contains 96 monthly series of plant capacity factors (32 for each load block), which are inputs to SDDP. The introduction of the NCEP-CSFR capacity factor series to describe the wind variability by load block is the only difference between the government plans and our baseline scenario. SDDP draws a lottery from those monthly series and optimizes the hydrothermal schedule according the wind energy output from the selected series. Because of the system constraints, wind curtailment might occur but should be avoided as it represents a waste of energy. Wind curtailment is one of performance indicators we compared across scenarios.

Table 4-3 describes the evolution of installed capacity by source in the baseline scenario from 2013 to 2028, as well as the modifications implemented in the alternative expansion scenarios. Most of the new thermal power plants are powered by natural gas (92% of the total new capacity in the baseline scenario). Additionally, two new nuclear power plants (Angra 3,
which is under construction, and another planned plant) correspond to 6% of the new thermal generation capacity in the baseline. Therefore, coal, diesel, and oil represent a just minor (~2%) share of the new capacity. In addition to the new capacity described in Table 4-3, the “Coal/Oil/Diesel Retirement” scenario includes the replacement of approximately 8 GW of coal, oil, and diesel power plants under operation by cleaner natural gas power plants. We assumed the Coal/Oil/Diesel power plants are replaced by natural gas power plants in the beginning of the simulation (May 2013).

Table 4-3: Additional capacity by year: baseline and alternative scenarios

<table>
<thead>
<tr>
<th>Year</th>
<th>Non-Amazon Hydro</th>
<th>Amazon Hydro</th>
<th>Thermal</th>
<th>Wind</th>
<th>Baseline Wind27</th>
<th>Wind39 and Coal/Oil/Diesel Retirement</th>
<th>Natural Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Additiona l Wind in relation to the baseline</td>
<td>Additional Wind in relation to the baseline</td>
<td>Additi onal Natural Gas in relation to the baseline</td>
</tr>
<tr>
<td>2013</td>
<td>422</td>
<td>1,203</td>
<td>2925</td>
<td>0</td>
<td>1,203</td>
<td>0</td>
<td>1,203</td>
</tr>
<tr>
<td>2014</td>
<td>111</td>
<td>2,605</td>
<td>1343</td>
<td>0</td>
<td>2,605</td>
<td>0</td>
<td>2,605</td>
</tr>
<tr>
<td>2015</td>
<td>0</td>
<td>4,554</td>
<td>1102</td>
<td>3,750</td>
<td>4,554</td>
<td>0</td>
<td>4,554</td>
</tr>
<tr>
<td>2016</td>
<td>674</td>
<td>4,570</td>
<td>0</td>
<td>3,000</td>
<td>4,570</td>
<td>0</td>
<td>4,570</td>
</tr>
<tr>
<td>2017</td>
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<td>3,886</td>
<td>316</td>
<td>1,500</td>
<td>3,886</td>
<td>0</td>
<td>3,886</td>
</tr>
<tr>
<td>2018</td>
<td>45</td>
<td>4,767</td>
<td>1705</td>
<td>1,500</td>
<td>4,767</td>
<td>0</td>
<td>4,767</td>
</tr>
<tr>
<td>2019</td>
<td>328</td>
<td>611</td>
<td>0</td>
<td>1,500</td>
<td>611</td>
<td>0</td>
<td>611</td>
</tr>
<tr>
<td>2020</td>
<td>1018</td>
<td>945</td>
<td>0</td>
<td>750</td>
<td>0</td>
<td>750</td>
<td>0</td>
</tr>
<tr>
<td>2021</td>
<td>290</td>
<td>2,533</td>
<td>0</td>
<td>750</td>
<td>0</td>
<td>3,000</td>
<td>0</td>
</tr>
<tr>
<td>2022</td>
<td>619</td>
<td>2,155</td>
<td>0</td>
<td>750</td>
<td>0</td>
<td>2,250</td>
<td>0</td>
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<tr>
<td>2023</td>
<td>819</td>
<td>2,419</td>
<td>0</td>
<td>1,500</td>
<td>0</td>
<td>2,250</td>
<td>0</td>
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<tr>
<td>2024</td>
<td>1292</td>
<td>4,235</td>
<td>0</td>
<td>1,500</td>
<td>0</td>
<td>4,500</td>
<td>0</td>
</tr>
<tr>
<td>2025</td>
<td>347</td>
<td>4,818</td>
<td>1000</td>
<td>2,250</td>
<td>0</td>
<td>5,250</td>
<td>0</td>
</tr>
<tr>
<td>2026</td>
<td>567</td>
<td>2,801</td>
<td>0</td>
<td>2,250</td>
<td>0</td>
<td>3,000</td>
<td>0</td>
</tr>
<tr>
<td>2027</td>
<td>1135</td>
<td>2,326</td>
<td>1300</td>
<td>3,000</td>
<td>0</td>
<td>2,250</td>
<td>0</td>
</tr>
<tr>
<td>2028</td>
<td>948</td>
<td>1,821</td>
<td>10300</td>
<td>2,250</td>
<td>0</td>
<td>2,250</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>8,658</td>
<td>46,247</td>
<td>19,990</td>
<td>26,250</td>
<td>22,195</td>
<td>25,500</td>
<td>53,250</td>
</tr>
</tbody>
</table>

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4.3.4. Performance indicators

We compared the baseline and the alternative scenarios using technical, economic, and environmental performance indicators. Land use and greenhouse gas emissions are the environmental impact metrics of interest for this chapter. Direct land use requirements (excludes transmission lines) for new projects were calculated using the following assumptions:

- Large hydro power reservoirs: sum of the reservoir areas
- Wind: 0.003 MW/km$^2$.
- Thermal electricity from coal and natural gas: 0.035 MW/km$^2$.

GHG emissions from hydropower are usually low; however, reservoirs located in tropical forested areas have the potential to emit large quantities of methane, a more powerful GHG gas compared to carbon dioxide. Carbon dioxide (CO$_2$) and methane (CH$_4$) emissions from hydropower result from the oxic/anoxic decomposition of the flooded organic matter from different sources within the reservoir (e.g. vegetation and soils) and from outside the reservoir (e.g. sedimentary OM input from the upstream river basin). Estimates for eighteen new hydropower plants planned in the Amazon indicate total emissions that vary from 9-21 Tg of CH$_4$ and 81-310 Tg of CO$_2$ over a hundred years. Based on the average lower and upper bounds values defined by Faria et al. 2015, we estimated the emissions from eighteen major Amazon reservoirs (Belo Monte, Bem Querer, Cachoeira do Caí, Cachoeira do Caldeirao, Cachoeira dos Patos, Colider, Ferreira Gomes, Jamanxim, Jatobá, Jirau, Marabá, Salto Augusto de Baixo, Santo Antônio, São Luís do Tapajos, São Manoel, Sao Simao Alto, Sinop, and Teles Pires) over the first 15 years of operation that are within the scope of this study.
GHG emissions from thermal plants were calculated using the following emission factors:

- Nuclear: 16 t CO₂e/MWh
- Oil/Diesel: 840 t CO₂e /MWh
- Natural Gas: 470 t CO₂e /MWh
- Biomass: 40 t CO₂e /MWh
- Coal: 1,000 t CO₂e /MWh

Moreover, we compared the alternative scenarios in terms of investment costs for the new power plants and operating costs of the thermal system. Appendix C contains more details about this calculation. The EPE database provides the operation costs for each thermal power plant, which vary from 20 to 1,000 reais per MWh (6 to 285 US dollars per MWh). We assumed the same operational costs defined by EPE (250 reais/MWh, 70 US$/MWh) for the new natural gas power plants.

To evaluate the hydro performance of each alternative, we also compared the energy storage levels in the hydroelectric reservoirs, which is a measure of the system resilience against droughts. This value is calculated using the volume of water stored in each reservoir with storage capacity multiplied by its average production coefficient (MWh/m³). Further, we used the wind curtailment levels in megawatts as an indicator of the system performance.

### 4.4 Results and Discussion

#### 4.4.1 Generation output projections

Figure 4-3 describes the optimal generation output for each scenario from May 2013 to December 2028 by load block and fuel type. The coloured areas in Figure 4-3 define the average
power output considering 400 simulations of the optimal system operation. In December 2013, wind power represents just 3% of the total generation (5% of the total capacity), while the total renewable generation (including large hydro) accounts for 80% of the total generation.

In the baseline scenario, 46 GW of hydropower plants in the Amazon fulfil most part of the future electricity demand. Wind generation plays a minor role in this scenario and, in 2028 wind power corresponds to only 15% of the total installed capacity (on average, 12% of the total generation in December 2028). Average hydropower output varies by load block indicating that these plants are dispatched to balance the load variability. In contrast, average thermal generation does not vary significantly by load block, and the power plants are dispatched with the same power output within the day (“base load”). The wet-dry season variability explains the peaks and valleys in the hydro and thermal generation. The limitation of water resources during the dry season (April-September) reduces the hydropower generation capacity and more thermal generation is necessary to meet demand. In December 2028, renewables sources (including large hydropower) represent 80% of the total generation. Thus, the baseline results indicate the same level of renewable generation throughout the study horizon.

The major difference between scenario “Wind27” and the baseline is the higher penetration of wind in the system after 2020. In December 2028, wind accounts for 20% of total generation, while the total renewable generation represents 84% of total. Most of the new wind plants are located in the Northeast subsystem where higher wind speeds occur from July to November. These higher wind speeds occur in July/August as the dry season peaks (when hydropower output decreases), thus maintaining thermal generation as base load. However, as
the penetration of wind increases to 24% of installed capacity (2025), thermal generation starts to vary significantly by demand block to balance the daily wind variability.

Scenario “Wind39” presents a more aggressive policy towards wind generation. It characterizes an expansion scenario where wind replaces all 46 GW of recently built, under construction, and future hydropower plants in the Amazon. The major difference between the operating profiles in scenario “Wind39” and the baseline is the change in the thermal generation profile. From 2013 to 2018, wind power replaces large power plants in the Amazon like Jirau, Santo Antonio, and Belo Monte and average thermal generation decreases and continues to be dispatched as base load. By 2020, wind account for 28% of total installed capacity, and thermal power plants start being dispatched to meet high and medium demand periods during the low wind speed season (February-June). Between 2020 and 2028, average thermal generation also increases faster compared to the baseline and the “Wind27” scenarios. In December 2028, wind and total renewable generation account, on average, for 29% and 84% of the total electricity generated in the system, respectively. The “Coal/Oil/Diesel Retirement” average dispatch profile is similar to the “Wind39”.

In the last scenario, natural gas power plants (rather than wind) replace the same hydropower plants as in the “Wind27” scenario. Wind capacity in this scenario increases as in the baseline scenario. The lack of significant additional capacity from hydro or wind power plants in this scenario increases the average demand for thermal generation. After 2024, the thermal generation seasonal variability also increases because there is no wind to compensate for the seasonal changes in hydropower output. Furthermore, after 2024, when wind power accounts for 13% of the total installed capacity, the quantity of thermal generation necessary to supply the
demand peak (high demand block) increases. In December 2028, total renewables generation corresponds to 75% of the total generation, representing the lowest share across the scenarios.
Figure 4-3: Average optimal dispatch for each scenario by source (wind, hydro and thermal power plants) and by load block (high, medium, load).
4.4.2 Energy storage

The quantity of water stored in the reservoirs is a pertinent performance indicator because storage adds resilience against droughts (seasonal variability) and flexibility to meet daily load variability. Figure 4-4 summarizes the energy storage in hydropower reservoirs during the study horizon for each scenario, measured as a percentage of total system storage capacity. For a given month, the energy storage is defined by the multiplication of the volume in each reservoir by its production coefficient taking into account the cascade of hydropower plants.

There are two sorts of variability represented in Figure 4-4. The first source of variability is the seasonal variability, which is illustrated by the average lines. The dry-wet seasons explain the peaks and valleys in the average energy storage profile in Figure 4-4. During the wet season, inflows tend to be above the annual average and the system operator manages the power plants dispatch to fill the storage reservoirs. On the other hand, inflows are below the annual average in the dry season, but the operator can use stored water from the reservoir to increase hydropower production to displace thermal generation.

The second variability is associated to the random inflows process over time. The stochastic process variability is captured in the model by simulating each expansion plan over the study horizon 400 times using different inflows series. As a result, SDDP output contains a distribution of the optimal dispatch under those 400 hundred simulated conditions. The shading defines the 95% confidence interval of the energy storage from the 400 simulated operations and characterizes the storage variance. Note that the wind seasonal and stochastic variability are also incorporated into the model affecting the optimal dispatch and, as a consequence, the storage levels.
By 2028, the seasonal variability of the hydro storage operations increase in the baseline scenario because of the greater seasonal variability integrated into the system by the large planned run-of-river hydropower plants in the Amazon without a proportional increase in storage capacity. These run-of-river designs aim to reduce the reservoir area (and volume) mitigating environmental and social impacts from the reservoir creation, at the cost of no storage capacity. Replacing Amazonian hydro with natural gas plants (Natural Gas scenario) reduces the system’s capacity to store water but also reduces the storage variation between peaks and valleys compared to the baseline scenario.

The replacement of Amazonian hydropower by wind power plants has two major consequences to energy storage: 1) a reduction in the average storage variability between low and dry seasons because of the negative correlation between wind and inflows, and 2) an increase in the energy storage variance because of the wind/inflows stochastic features. Both characteristics are clear in the “Wind39” scenario, where the distance between average storage peaks and valleys is lower than the baseline, and the red shade is “thicker” indicating a higher variance compared to the baseline. The higher variance implies that storage capacity variability is higher under a high wind penetration. It happens because now the system operator needs to deal with two sources of electricity that present a random process: hydropower and wind. A system with high hydro and wind penetration is subject to more electricity output variability than a system with high hydro and low wind penetration. A similar but less evident effect occurs in the “Wind27” scenario after 2025 when the wind generation becomes more prominent.
Figure 4-4: Average (lines) storage capacity in hydropower reservoir for each scenario presented in terms of the percentage of the total storage capacity. The shades represent the 95% confidence interval from 400 hundred simulation for each scenario. “Coil/Oil/Diesel Retirement” scenario has the same storage profile as the “wind39” scenario.

4.4.3 Wind curtailment and lost load

The probability of wind curtailment and the probability of lost load are also relevant technical performance indicators of an electric system. To calculate wind curtailment in the optimization, we created an elastic demand variable with a zero cost to “absorb” wind overproduction. In contrast, the lost load is defined by the ratio (in percentages) between the
energy (in GWh) that the system was not able to supply and the total demand (in GWh). Figure 4-5 describes the cumulative distribution results for lost load and wind curtailment.

The central characteristic of the lost load distributions is the low probability of significant lack of energy during the study horizon. We developed the alternative scenarios to provide approximately the same reliability levels as those in the baseline scenario, measured by lost load. Figure 4-5 shows that 99% of the time there is no lost load. The highest lost load levels occur only when the system faces a sequence of seasons with low wind speeds and little precipitation in the “Wind39” scenario.

The probability of wasting energy through wind curtailments is higher in the “Wind39” and “Coal/Oil/Diesel Retirement” scenarios because of the higher wind penetration. The simulation results indicate zero wind curtailment for just 60% of the time for those scenarios (Figure 4-5). Wind curtailment typically happens during the period of low loads, high wind speed seasons, and when the reservoirs are already filled and there is no more capacity to store water. The baseline and “Wind27” scenarios have similar empirical distributions for wind curtailment. For those scenarios, the energy curtailed is close to zero during 87% of the time. The lower wind and hydropower penetration in the “Natural Gas” scenario leads to the lower probability of wind curtailment across the expansion scenarios.
Figure 4-5: Cumulative distribution functions (CDF) of lost load (as a percentage of the total demand) and wind curtailment (in GWh) by scenario and load block.
4.4.4 Costs

We estimated the investment and operational costs of building the new power plants for each scenario. Table 4-4 summarizes the results and describes the capital costs, annual operational and maintenance (O&M) costs, and the annualized costs (Appendix C contains the calculation details for each source). The results indicate that the baseline and “Wind27” scenario have similar construction costs of around 300 billions reais (approximately 86 billion dollars). We estimated the cost of the hydropower plants using the project costs at the capacity auctions held by the Chamber of Electric Energy Trading (CCEE) and, thus, represent pre-construction estimates. However, large hydropower projects have historically suffered cost overruns, estimated at 96% globally\(^\text{32}\). In Brazil, for example, the Belo Monte hydropower plants was expected to cost 18 billions reais (approximately US$ 5 billion), but the actual cost was over 30 billion reais (approximately 9 billion US dollars). Considering a 50% and 96% cost overrun across the Amazonian hydropower projects, the capital costs in the baseline scenario would increase to an actual cost of 360 to 405 billion reais (100 to 115 billion US dollars), respectively. Total construction costs from the “Wind27”, “Wind39”, and “Coil/Oil/Diesel retirement” scenarios are 13%, 35% and 50% higher, respectively, than the baseline scenario. “Natural Gas” scenario construction costs are 20% cheaper than the baseline. Appendix C (section 8.5) provides details about the construction cost estimates.
Table 4-4: Construction, operation & maintenance (O&M), and annualized costs for each scenario

<table>
<thead>
<tr>
<th>Source</th>
<th>Installed Capacity (MW)</th>
<th>*Total Construction Costs (million reais)</th>
<th># Annual O&amp;M (million reais)</th>
<th>^Annualized costs(million reais)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amazon hydro</td>
<td>46,247</td>
<td>108,658</td>
<td>2,173</td>
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<tr>
<td>Non-Amazon hydropower</td>
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<td>29,995</td>
<td>600</td>
<td>4,212</td>
</tr>
<tr>
<td>Thermal</td>
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<td>58,025</td>
<td>14,500</td>
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</tr>
<tr>
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<td>105,000</td>
<td>2,100</td>
<td>14,744</td>
</tr>
<tr>
<td><strong>Total</strong></td>
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<td><strong>301,678</strong></td>
<td><strong>19,373</strong></td>
<td><strong>55,701</strong></td>
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<tr>
<td>Wind27</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amazon hydro</td>
<td>22,195</td>
<td>47,132</td>
<td>943</td>
<td>6,618</td>
</tr>
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<td>29,995</td>
<td>600</td>
<td>4,212</td>
</tr>
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<td>Amazon hydro</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>Non-Amazon hydropower</td>
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<td>29,995</td>
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</tr>
<tr>
<td>Coal/Oil/Diesel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>retirement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amazon hydro</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Non-Amazon hydropower</td>
<td>8,657</td>
<td>29,995</td>
<td>600</td>
<td>4,212</td>
</tr>
<tr>
<td>Thermal</td>
<td>27,707</td>
<td>104,537</td>
<td>30,300</td>
<td>42,888</td>
</tr>
<tr>
<td>Wind</td>
<td>79,500</td>
<td>318,000</td>
<td>6,360</td>
<td>44,654</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>115,863</strong></td>
<td><strong>452,532</strong></td>
<td><strong>37,260</strong></td>
<td><strong>91,754</strong></td>
</tr>
</tbody>
</table>

* Total construction costs are calculating considering the currency in reais on May, 2015
# Wind and hydropower power plants annual O&M costs are estimated in 2% of the total construction costs/ Thermal power plants O&M cost are calculated using the average annual O&M costs for the entire system according to the optimal dispatch in 2028. O&M costs for each thermal power plant are defined in the Appendix C and includes fuels costs.
^ We annualized the capital and O&M costs by assuming that the power plants have a lifetime of 50 years, and internal rate of return of 12%, which is equal to calculate: construction costs* 0.12042 + Annual O&M

To compare both construction and O&M costs in the same metric, we annualize the construction cost and sum this result with the annual O&M costs (including fuel costs) resulting in total annualized cost of building and operating the system. The annualized costs (last column
in Table 4-4) show that the baseline has the lowest annualized cost (56 billion reais, 15 billion dollars) when hydropower cost overrun is not incorporated in the calculation. Considering a cost overrun from 50% to 96% over the Amazon hydropower plants, the annualized cost would increase from 63 to 70 billion reais (18 to 20 billion dollars). Annualized costs from the “Wind27”, “Wind39”, “Natural Gas”, and “Coil/Oil/Diesel Retirement” scenarios are 15%, 54%, 40%, and 64% more expensive, respectively, than the baseline scenario.

Another indicator that is often applied to define the electric system costs is the operational marginal cost. The marginal cost is a SDDP output defined by the change in the operating cost with respect to an infinitesimal change in the load (reais/MWh). Figure 4-6 presents the simulated marginal cost results for each scenario. The historically low levels of the hydroelectric reservoirs in the beginning of the simulation (initial conditions in 2013) explain the high values of the upper confidence bounds in the first four years of analysis (2013-2016). Marginal costs are higher when more thermal generation is used to replace hydropower.

The marginal cost projections show that the baseline, “Wind27”, and “Natural Gas” scenarios have similar marginal costs distributions with a median bellow or equal 250 reais/MWh (70 dollars/MWh) by 2028. The “Natural Gas” marginal costs variance, represented by the quartiles in the box plot, is lower than the baseline by the end of the analysis because of the new natural gas power plants operating costs. We assumed that the marginal cost of operating those new plants is 250 reais/MWh (70 dollars/MWh), which is the value projected by the government in the EPE report files. The new natural gas power plants operating cost is lower than the majority of the older thermal power plants, displacing more expensive thermal and reducing the marginal costs variance in the “Natural Gas” scenario.
In contrast, scenarios “Wind39” and “Coal/Oil/Diesel retirement” present a distinct average marginal cost profile because of the higher wind penetration, especially in the second half of the period of analysis. After 2020, the dispatch of thermal power plants increases during the low wind season, increasing the system marginal costs, especially during high load. By 2028, median marginal cost for both “Wind39” and “Coal/Oil/Diesel Retirement” are above the 250 reais/MWh (70 dollars/MWh).
Figure 4-6: Marginal costs (reais/MWh) by year: box-plots from the 400 simulations
4.4.5 Greenhouse gas emissions

In 2012, GHG emissions from thermal electricity generation were estimated in 48.5 Tg of CO₂eq. According to the Intended Nationally Determined Contributions (INDCs) presented to the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP21) in Paris in December 2015, Brazil intends to reduce GHG emissions by 43% below 2005 levels by 2030. Brazilian GHG emissions in 2005 are estimated in 210 Tg CO₂eq. Among others, one of the measures to achieve the emissions reduction target is to expand the share of wind, biomass, and solar in the power system to at least 23% by 2030.

Figure 4-7 describes the total direct annual emissions from thermal power plants projected for each scenario (Box-plots). In the first complete year of analysis (2014), average annual direct emissions total 47 Tg of CO₂eq (95% CI: 21-99). In the baseline scenario direct emissions increase to 56 Tg of CO₂eq (95% CI: 26-103) in 2028, when the share of wind, biomass, and solar in the total power capacity is 18% (below the INDC value).

The “Wind27”, “Wind39”, and “Natural Gas” scenarios also result in increased direct GHG emissions from power generation between 2014 and 2028, and by 2028 such emissions would be higher than in the baseline scenario. In 2028, direct emissions from the “Wind27” scenario total 63 Tg of CO₂eq (95% CI: 30-107) when the share of non-hydro renewables is 30% of the total capacity. In the “Wind39” scenario, the higher renewables share (40% excluding hydro) leads to even higher GHG emissions that are estimated in 83 Tg of CO₂eq (95% CI: 47-118) in 2028. These results indicate that direct GHG emissions from the Brazilian power system will likely increase by 2028 under government plans, even as Amazonia hydro capacity grows. Furthermore, replacing the Amazonian hydropower plants with wind could even increase direct
emissions from the power sector. These increases in direct GHG emissions occur because more thermal power generation is necessary to meet demand during dry and low wind speed seasons.

Not surprisingly, the “Natural Gas” scenario results in the highest direct annual GHG emissions (102 Tg of CO$_2$eq in 2028; 95% CI: 60-159) due to the increase in the thermal capacity. The “Coal/Oil/Diesel retirement” scenario evaluates the impact of replacing dirtier fossil fuel power plants by natural gas assuming the same level of wind penetration of the “Wind39” scenario. The exclusion of the dirtier fossil fuel power plants would reduce emissions in 2028 from 83 Tg of CO$_2$eq (95% CI: 47-118) in the “Wind39” to 73 Tg of CO$_2$eq (95% CI: 38-105) in the “Coal/Oil/Diesel Retirement” scenario. Those values do not include methane emissions from natural gas production, processing, and distribution, which have been shown to be significant$^{35,36}$. 
Figure 4-7: Box-plots: annual direct greenhouse gas (GHG) emissions from power generation by scenario (only thermal power plants). Total system emissions include GHG emissions from new Amazon reservoirs plus total direct emissions in the study horizon. The baseline Amazon GHG emissions include the results from the eighteen hydropower plants defined by Faria et al. 2015. “Wind27” and “Natural Gas” scenarios include only the emission from those eighteen hydropower plants build before 2020. Orange diamonds represent the mean.
The box-plot results described in Figure 4-7 are limited to direct emissions from the power system that result from combustion of fossil fuels and do not include emissions associated with the degradation of the biomass in new Amazon hydropower reservoirs. Although there is significant uncertainty in estimates of GHG emissions from Amazon reservoir, using the values reported in Faria et al 2015, we estimate that the new major hydropower plants in the Amazon would emit an additional 25 to 300 Tg of CO$_2$eq into the atmosphere over the first 15 years of operation. While these emissions are still lower than the total direct emissions, they are not insignificant and further demonstrate that emissions associate with power generation could continue to increase by 2028 even if new renewable capacity is added to the system.

In Figure 4-7, we also estimate the expected total system emissions of each scenario across the study horizon considering hydropower emissions from new Amazonian reservoirs. The total system emissions consists in the sum of the annual direct emissions plus an average emissions from new Amazon hydropower plants (top-down and bottom-up models from Faria et al 2015). The results indicate that the “Coal/Oil/Diesel Retirement” scenario (which includes 40% wind) has the lowest GHG emissions (710 Tg of CO$_2$eq), followed by “Wind27” and “Wind39” (both with 860 Tg of CO$_2$eq). The baseline scenario results in a total GHG emission of 920 Tg of CO$_2$eq between 2013 and 2028. As expected, the “Natural Gas” scenario has the highest total system emissions (1000 Tg of CO$_2$eq).

4.4.6 Land use

Land use requirement for new power plants can serve as a proxy of non-climate related environmental and social impacts of generating capacity expansion. Table 4-5 describes the land
use requirements for each scenario. Because of the reservoirs, hydropower plants require the most land. The construction of all hydropower plants in the Amazon would require 9,000 km$^2$ (to give a special perspective, this is 840 thousand soccer fields), resulting in a total land use requirement of approximately 9,800 km$^2$ in the baseline when accounting for all sources. The replacement of Amazon hydropower plants planned to be built after 2020 by wind parks and thermal power plants would reduce the total land use requirements by approximately 7,200 and 6,800 km$^2$, respectively.

| Table 4-5: Land use requirements for each scenario by source (km$^2$) |
|-----------------|------|-----|-----|-----|
|                 | Amazon hydropower | Wind | Thermal | Total |
| Baseline        | 9,000 | 80  | 700  | 9,780 |
| Wind27          | 1,700 | 160 | 700  | 2,560 |
| Wind39 and Coal/Oil/Diesel retirement | 0   | 240 | 700  | 940   |
| Natural Gas     | 1,700 | 80  | 1,200 | 2,980 |

4.5 Summary, policy implications and limitations

To condense our findings and present an overall comparison between scenarios, we summarize each performance indicator across the scenarios (Table 4-6). The system represented in the starting date (May 2013) has 83% of renewable capacity, but only 12% when excluding large hydropower plants. Except for the “Natural Gas” scenario, Table 4-6 shows that the proportion of renewable capacity in 2028 corresponds to 83% of the total capacity, a similar value compared to the renewables fraction in 2013. However, the share of renewables excluding large hydropower plants varies significantly across the expansion plans scenarios affecting the performance indicators.
This chapter compares key performance indicators for an expanded power system in Brazil relying on different sources, including hydropower plants in the Amazon, wind, or natural gas power plants. Although our scenarios are extreme as we assume complete replacement of one source by another, they have the advantage of underscoring the consequences of choosing one “winner” and its main effect on system operation and costs. The outcomes comparison in Table 4-6 suggests that the optimal energy mix is likely a hybrid of lower impact hydropower plants, wind and natural gas - more similar to scenario “Wind27” than the baseline.

Our results indicate that when the wind share grows from 24% to 28% of total installed capacity, the fossil fuel thermal power plants start cycling more often, thus increasing marginal costs and GHG emissions. In order to achieve significant emissions reduction in the electric sector, Brazil would have to include other alternatives. One option would be replace part of the dirtier fossil fuel power plants by new natural gas or nuclear power plants. The comparison between the “Wind39” and “Coal/Oil/Diesel Retirement” scenarios shows that the replacement of the old coal, oil, and diesel power plants by new natural gas power plants would reduce total system emissions by 28% between 2013 and 2028. Another options would be increasing storage

<table>
<thead>
<tr>
<th>Performance indicators</th>
<th>Baseline</th>
<th>Wind27</th>
<th>Wind39</th>
<th>Natural Gas</th>
<th>Coal/Oil/Diesel Retirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Share of renewable power in the system in 2028 (%)</td>
<td>82%</td>
<td>82%</td>
<td>82%</td>
<td>74%</td>
<td>82%</td>
</tr>
<tr>
<td>Share of renewable power in the system excluding hydropower in 2028 (%)</td>
<td>18%</td>
<td>30%</td>
<td>40%</td>
<td>19%</td>
<td>40%</td>
</tr>
<tr>
<td>Annualized costs (billion reais)</td>
<td>56</td>
<td>60</td>
<td>82</td>
<td>68</td>
<td>88</td>
</tr>
<tr>
<td>Annualized costs considering 50% hydropower cost overrun (billion reais)</td>
<td>65</td>
<td>63</td>
<td>82</td>
<td>72</td>
<td>88</td>
</tr>
<tr>
<td>Highest wind curtailment (ranking)</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Average energy storage (n Dec. 2028, percentage of the total storage capacity)</td>
<td>39%</td>
<td>43%</td>
<td>58%</td>
<td>37%</td>
<td>58%</td>
</tr>
<tr>
<td>Total system GHG emissions 2013-2028 (Tg CO2eq)</td>
<td>920</td>
<td>860</td>
<td>860</td>
<td>1,000</td>
<td>710</td>
</tr>
<tr>
<td>Land use (km²)</td>
<td>9,910</td>
<td>2,593</td>
<td>939</td>
<td>3,022</td>
<td>939</td>
</tr>
</tbody>
</table>
capacity by building low-impact storage reservoirs or rely on batteries and demand response mechanisms to reduce the thermal generation requirements in the peak loads.

Higher wind penetration also increases the supply variability at daily and seasonal scales such that the system operation complexity is greater. The wind variability issue should be more evident when modeling the system using a higher time resolution. We represented the daily variability using three demand blocks, which is a low resolution to represent the fast variations in wind or solar power output. Therefore, future research should increase the resolution and simulate the system using hourly or minute time steps. An important pre-condition for modeling improvements is the access to better wind and solar data. We thus suggest future efforts should focus on creating national database with high-resolution historical and simulated series of the wind speeds and energy output at higher temporal resolution than currently available.

Energy plans should not only focus on selecting one “winner” and only one pathway to follow. Capacity expansion studies should investigate the social, environmental, economic costs and benefits of building and operating new power plants by simulating and assessing several pathways to the future. This chapter underlines that hydroelectric development policy in the Amazon region deserves such a treatment.
References

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34. Brazil, F. R. O. Federative Republic of Brazil Intended Nationally Determined Contribution . 1–10 (Federative Republic of Brazil: 2015).
5. CONCLUSIONS AND POLICY RECOMMENDATIONS

The Brazilian government has proposed a significant expansion of hydropower plants in the Amazon in order to fulfill future electricity demand. The size of the investments (30 to 60 billion dollars by 2028) and the necessary area to build the reservoirs (9,000 km$^2$) illustrate the magnitude of the Amazon hydropower development policy. However, it is not clear that building hydropower plants in the middle of the biggest tropical forest in the Earth is the most cost-effective alternative to meet the majority of future electricity requirements in Brazil. Although the construction of large hydropower plants has significant benefits, including the generation of relatively cheap electricity and job creation, there are also several social (e.g. people resettlement), economic (e.g., loss of Agricultural GDP) and environmental costs (e.g. loss of fauna and flora, GHG emissions).

Despite the extensive scientific literature about hydropower impacts, most of the studies are qualitative and there is a lack of quantitative assessment of the social, economic and environmental hydropower impacts, especially in developing countries. In this dissertation, I identified three major issues relative to hydropower development in the Brazilian Amazon and employed quantitative methods for policy analysis to advance the knowledge about those issues and support informed decision.

In Chapter 2, I examined the GHG emissions from recently build and planned hydropower reservoirs in the Amazon. I helped to expand the literature by proposing the first predictive model for estimating GHG emissions from hydropower reservoirs based on a Monte Carlo simulation structure. Although the uncertainty on GHG emissions from hydropower reservoirs is still high, through this work, I showed that it is possible to identify hydropower...
plants with a high probability to emit significant levels of GHG emissions supporting future project selection.

In Chapter 3, I investigated the relationship between hydropower development and local socio-economic indicators using 56 Brazilian hydropower plants built over 1991-2010 applying econometric methods. I found that counties that built hydropower plants had greater GDP and tax revenues during the first years, but those positive economic effects lasts less than 15 years. I also found that that social indicators in counties that built hydropower did not statistically differ from those in the control counties. I showed, in particular, that the agricultural sector is negatively affected by hydropower development, especially by large dams. This is a critical contribution of the chapter given that most of the regions affected by dams are rural areas, and the negative impact on the agricultural sector significantly attenuates the positive economic impacts observed on the local industry and services sectors.

In Chapter 4, I simulated the operations of the Brazilian electric system operation under five capacity expansion scenarios. I found that wind energy has the potential to replace at least part of future hydropower plants in the Amazon at the same cost levels, bringing additional advantages to the electric system (e.g. increase average energy storage) and reducing land use requirements. However, I show that there is a limit for the wind expansion that varies from 24% to 28%. After this range, fossil fuel thermal power plants start cycling more often, increasing marginal costs and GHG emissions. My findings emphasize the need of including alternative scenarios in future capacity expansion plans.

Finally, this Dissertation underscores that there is a lack of understanding about the full costs and benefits of developing large hydropower plants in the Amazon. Analyzes of the costs and benefits of hydropower projects in Brazil has been restricted to the direct costs (e.g.,
construction costs) and direct benefits (e.g. electricity produced). This Dissertation stresses the need for accounting for indirect costs, such as the negative effect on the Agricultural GDP caused by large dams (Chapter 3). There is a lack of methods to assess and quantify the loss of ecosystem products and ecosystem services caused by hydropower plants. Scientist and engineers should fulfill this knowledge gap. My dissertation presents three examples on how quantitative methods for policy analysis (Monte Carlo simulation, econometrics, and optimization) can help to fulfill this gap. While the work in this thesis resulted in new quantitative information about the trade-offs associated with the expansion of the Brazilian hydropower system, there are still several unanswered questions about the impacts of new hydropower development. For instance, does the migration of people looking for new opportunities increase deforestation levels around hydropower projects? What are the impacts of climate change on precipitation patterns and their consequences on inflows and energy production? These unanswered questions should serve as motivation for future research that supports the design and operation of robust electricity systems under climate constraints.
6. APPENDIX A: CHAPTER 2
6.1 Model Details

This document includes details about the data and methods described in Chapter 2, as well as complementary results and discussion.

Figure S1 presents a representation of the main processes that lead to greenhouse gases (GHG) emissions. The figure describes the major sources of organic matter (OM) in the reservoir, as well as the production, consumption, and emissions of carbon dioxide (CO₂) and (CH₄) to the atmosphere.

![Figure S1: Scheme of GHG production (including OM sources), consumption and emissions to the atmosphere.](image)

CO₂ and CH₄ production in tropical reservoirs results from the oxic/anoxic decomposition of OM from many sources, such as the flooded vegetation and soil, OM allochthonous (sedimentary) input from upstream, and macrophytes and algae produced in the reservoirs (Abril et al. 2005; Demarty & Bastien 2011; Guérin et al. 2008). The main pathways of GHG emissions to the atmosphere include ebullitive fluxes, diffusive fluxes from the water.
surface of the reservoir, degassing right after the dam outlets structures (e.g. turbines, spillways), and fluxes through the downstream river.

Two temporal stages characterize the carbon (C) emissions from reservoirs. During the first stage, decomposition of easily decomposable biomass (like soil micro fauna and green parts of the vegetation) in the flooded area drives a sharp increase of emissions during the first few years. During the second phase, emissions tend to be reduced as the system reaches a steady state (St. Louis et al. 2000; Galy-Lacaux et al. 1999; Rosa et al. 2004; Demarty & Bastien 2011). The steady state results from shifts in the balance between the decomposition of flooded biomass at the reservoir bottom and CO₂ uptake by the phytoplankton in the epilimnion (the uppermost layer in a stratified reservoir)(Abril et al. 2005). Data from tropical reservoirs suggest that steady state conditions occur a few years (3 to 10 years) after reservoir creation (flooding), and that most of the emissions in this second stage continue to be derived from the flooded C pool in the reservoir area (Abril et al. 2005; Demarty & Bastien 2011; Guérin et al. 2008; Delmas, Galy-Lacaux & Richard 2001). For example, flooded biomass was still available in Petit Saut and Balbina 10 and 23 years after flooding, respectively (Abril et al. 2012).

We developed two independent approaches based on a Monte Carlo simulation structure to estimate CO₂ and CH₄ emissions in Amazonian reservoirs. The top-down (TD) approach relies on flux data measured in tropical reservoirs and rivers in South American equatorial forests. In the TD approach we modeled reservoir emissions, degassing emissions, downstream emissions, and natural river emissions (before flooding). The bottom-up (BU) approach is based on the potential emissions derived from the degradation of the removed and flooded OM in the reservoir areas, considering GHG production rates and CH₄ oxidation in the water column.
6.1.1 Top-down approach

We divided the GHG emissions from reservoir in two systems: the river system (before flooding) and the reservoir system (after flooding). The river system represents the environment before the reservoir construction, which is related to the natural conditions within the model boundaries. Rivers and wetlands in the Amazon are natural C sources as they transport, respire, and outgas C originating from OM from upland and flooded forests (Richey et al. 2002). The reservoir system characterizes the environment after the dam construction. The beginning of the reservoir in the upstream side defines the upper boundary of each system, which extends a 40km river distance downstream the dam. The differences in the fluxes to the atmosphere between the reservoir system and the river system define the reservoir net GHG emissions (NRE) (Equation S1).

\[
\text{NRE} = \text{Reservoir} + \text{Degassing} + \text{Downstream} - \text{Natural}
\]  

(S1)

Where, Reservoir represents the total annual surface emissions from the reservoir, defined by the annual CO\(_2\) (Res\(_{\text{CO2}}\)) and CH\(_4\) (Res\(_{\text{CH4}}\)) reservoir emissions. Degassing represents the total annual outlet degassing emissions and includes emissions of CO\(_2\) (Deg\(_{\text{CO2}}\)) and CH\(_4\) (Deg\(_{\text{CH4}}\)). Downstream represents the total annual emissions downstream the reservoir and includes emissions of CO\(_2\) (Down\(_{\text{CO2}}\)) and CH\(_4\) (Down\(_{\text{CH4}}\)). Natural represents the total annual emissions from the river in its natural state and also includes CO\(_2\) (Nat\(_{\text{CO2}}\)) and CH\(_4\) (Nat\(_{\text{CH4}}\)).

The GHG flux (daily flux mass per unit of area) multiplied by the surface area and number of days in the year defines the total annual emissions for each pathway (Res, Deg, Down and Nat) according to the equations S2 to S5.
Reservoir = Res\(_{\text{CO}_2}\) + Res\(_{\text{CH}_4}\) = \([A_{\text{RES}} \times \text{res}\_{\text{CO}_2}) + (A_{\text{RES}} \times \text{res}\_{\text{CH}_4})]\) x 365 \hspace{1cm} (S2)

Degassing = Deg\(_{\text{CO}_2}\) + Deg\(_{\text{CH}_4}\) = \([A_{\text{RES}} \times \text{deg}\_{\text{CO}_2}) + (A_{\text{RES}} \times \text{deg}\_{\text{CH}_4})]\) x 365 \hspace{1cm} (S3)

Downstream = Down\(_{\text{CO}_2}\) + Down\(_{\text{CH}_4}\) = \([A_{\text{RIVERDOWN}} \times \text{down}\_{\text{CO}_2}) + (A_{\text{RIVERDOWN}} \times \text{down}\_{\text{CH}_4})]\) x 365 \hspace{1cm} (S4)

Natural = Nat\(_{\text{CO}_2}\) + Nat\(_{\text{CH}_4}\) = \([A_{\text{RIVER}} \times \text{nat}\_{\text{CO}_2}) + (A_{\text{RIVER}} \times \text{nat}\_{\text{CH}_4})]\) x 365 \hspace{1cm} (S5)

Where, res\(_{\text{CO}_2}\) and res\(_{\text{CH}_4}\) are the CO\(_2\) and CH\(_4\) reservoir emission fluxes, respectively. deg\(_{\text{CO}_2}\) and deg\(_{\text{CH}_4}\) are the CO\(_2\) and CH\(_4\) outlet degassing emission fluxes, respectively. down\(_{\text{CO}_2}\) and down\(_{\text{CH}_4}\) are the CO\(_2\) and CH\(_4\) downstream emission fluxes, respectively. nat\(_{\text{CO}_2}\) and nat\(_{\text{CH}_4}\) are the CO\(_2\) and CH\(_4\) natural river emission fluxes, respectively. All these fluxes are derived from empirical data, as discussed later in this document. A\(_{\text{RES}}\) is the reservoir area. A\(_{\text{RIVERDOWN}}\) is the river surface area downstream the dam, where the dam defines the upper limit, while a 40km distance downstream the dam defines the lower limit. A\(_{\text{RIVER}}\) is the river surface area within the model boundaries. We presented the fluxes in milligrams of the GHG gas per square meter per day (e.g. mg CH\(_4\) m\(^2\) day\(^{-2}\)) and the surface areas in square kilometers. Thus, we multiplied the surface areas by 10\(^6\) to obtain the annual emissions in grams. To convert the values from grams of the GHG to grams of C, we multiplied the results by the ratio of the atomic mass: 12/44 and 12/16 for CO\(_2\) and CH\(_4\), respectively.

Instead of applying conventional averages or ranges, we calculated the net reservoir emissions (NRE) using a Monte Carlo Simulation structure. Under this structure, the fluxes (res\(_{\text{CO}_2}\), res\(_{\text{CH}_4}\), deg\(_{\text{CO}_2}\), deg\(_{\text{CH}_4}\), down\(_{\text{CO}_2}\), down\(_{\text{CH}_4}\), nat\(_{\text{CO}_2}\) and nat\(_{\text{CH}_4}\)) are sampled from specific probability distributions; each sample set corresponds to one input scenario. Then, this input scenario is the basis to calculate the NRE and obtain one output scenario.

Each simulation corresponds to an annual steady state scenario NRE. Based on the emissions profile during the first ten years after flooding in Petit Saut (Abril et al. 2005), we
modeled the first pulse of emissions by applying a multiplier factor to the annual steady state scenario. The multiplier factors for the reservoir system in the first five years are: three times the steady state emissions for the first three years, and two times the steady state emissions for the fourth and fifth years. After the fifth year, the annual emissions are assumed to be constant. Thus, the total net reservoir emissions in a hundred years are defined by the sum of the emissions in the first pulse (first five years) plus the steady state emissions during the next 95 years.

We repeat the whole process 10,000 times, producing 10,000 independent scenarios with corresponding output values. Therefore, the model results directly relate to the field data measurements compiled in this chapter and the adjusted probability distributions (See Section Data Analysis). One advantage of this method is the possibility to treat the uncertain derived from the flux data variability in an explicit and transparent form, through the application of standard statistical techniques (Morgan 1990).

We developed the simulation code using the open source language and environment for statistical computing and graphics “R” and its packages ggplot2 (Wickham 2009). The R code is available upon request.

To convert all fluxes into CO\textsubscript{2} equivalents (CO\textsubscript{2}eq), we used the 100-year and 20-year global CH\textsubscript{4} warming potential (GWP), which the IPCC reported as 34 and 86, respectively, in the 5th Climate Assessment Report (IPCC 2013).

We did not include pre-flooding terrestrial and post-flooding C burial fluxes in our estimates. Previous research suggests that mature forests are C neutral, as the gross production and community respiration ratio approaches 1 in old forests. In other words, emissions from respiration balance the uptake from photosynthesis (Odum 1969). Recent studies based on long-term monitoring have re-opened the discussion by demonstrating that old forests are not in
balance. In the case of the Amazon forest, the average change in the above-the-ground stock from 0.36 to 0.62 metric tons of C per hectare per year (36 to 62 g C m$^{-2}$ yr$^{-1}$) (Malhi 2010). However, changes in the soil C stocks are not included in these budgets (Sayer et al. 2011), because the knowledge about Amazon soils C dynamics is limited. Based on this uncertainty and low order of magnitude of potential sinks and emissions in mature forests in comparison to water related emissions, we did not model the behavior of the forests contained within the reservoir area before the impoundment.

Similarly, we did not include C burial in our estimates. Part of the organic C contained in the reservoir sediments can escape mineralization and accumulate in the reservoirs, resulting in a C sequestration within the reservoirs (Mendonça et al. 2012). It is very difficult to estimate the burial rates because of unknown and unconstrained factors that drive this process and the only theoretical model suggests that burial rates could vary from 1,000 to 4,000 g CO$_2$eq m$^{-2}$ yr$^{-1}$ in Amazon reservoirs (Mendonça et al. 2012). However, this estimate is based on long residence time lakes, which do not resemble the reservoir conditions of the new reservoirs in our database. Thus, we did not include the C burial in the balance because of lack of empirical data, and the high uncertainty about this process.

The TD approach has two sub models that account for limnological differences based on the stratification level of the reservoirs.

**6.1.1.1 Reservoirs with high residence time and periods of stratification (TD - High RT)**

The first model relies on fluxes from the classical “old” reservoirs of Tucuruí, Petit Saut, Samuel, and Balbina, which have average residence times (RT) of 50, 150, 115 and 350 days, respectively, and present long periods of stratification throughout the year (Abril et al. 2005;
Kemenes, Forsberg & Melack 2007; Guérin et al. 2006; Fearnside 2002). The section “Data Analysis” in this document includes a complete literature review of available flux data for the main GHG pathways in existing Amazonian hydropower reservoirs, which are the basis of the probability distributions that represent each flux component in the C balance of reservoirs in this model.

While the literature includes 141 estimates of CO₂ emissions and 89 estimates of CH₄ emissions in reservoirs across the world, these data showed that reservoirs located in the Amazon have significantly higher GHG emissions when compared to other non-Amazonian tropical and temperate reservoirs (Barros et al. 2011). For this reason, our statistical model (reservoir system) for reservoirs with high residence times only relies on data from four reservoirs built on tropical forest ecosystems in South America: Balbina, Petit Saut, Samuel, and Tucurui.

6.1.1.2 Low residence time reservoirs (TD - Low RT)

The GHG flux literature about low RT reservoirs is scarce when compared to high RT reservoirs. The only available long-term measurements in low RT reservoirs were made in Lake Wohlen, a 2-day RT reservoir in Switzerland, where total CH₄ emission was on average greater than 150 mg CH₄ m⁻² d⁻¹ (DelSontro et al. 2010). In the case of Amazonian reservoirs, there is a first order estimate for the Santo Antônio dam, located at Madeira River. The estimate is based on data from just one campaign that took place five months after the reservoir started to be filled (Fearnside 2015b). The existing literature, however, provides important information that can be used to model the uncertainty in low RT reservoirs in the Amazon.

Low RT reservoirs have different fluxes to the atmosphere compared to high RT reservoirs, because the main reservoir channel has well-mixed water columns (oxic conditions)
and limnological characteristics similar to river zones (StrašKrab 1973; Straškraba, Tundisi & Duncan 1993). In contrast to those of the high RT reservoirs, the main channels of low RT reservoirs do not stratify (see Section “Density Froude Number and Residence Time”). However, the bays and tributary zones of the low RT reservoirs are expected to stratify due to their lower flows in these areas. As a consequence, bays and tributary zones have higher CH₄ emissions than the main channel. The measurements in the Santo Antônio reservoir confirm this spatial variability (Fearnside 2015b). Thus, we divided the emissions estimates for low RT reservoirs in two different zones: main channel (ACHANNEL) and bays/tributaries (ABAYS).

Because there is limited empirical data for low RT reservoirs, our model uses natural flux data as a proxy for low RT reservoirs (main channel fluxes). This substitution is valid because, first, prior research reports that GHG emissions are more strongly correlated to water column characteristics than flooded substrates (Duchemin et al. 2000; Pacheco et al. 2015). Second, we calculated the Densimetric Froude Number and RT for each reservoir under different flow scenarios. The high F-number and the low RT confirm that the main channel of these reservoirs resemble river conditions (StrašKrab 1973; Straškraba, Tundisi & Duncan 1993). Finally, data from the Santo Antônio reservoir also supports the assumption that natural river fluxes are good proxies for main channel emissions from low RT reservoir. Fearnside’s (2015) data on fluxes from the Santo Antônio main channel (3 mg CH₄ m⁻²d⁻¹) have the same order of magnitude as emissions average (10 mg CH₄ m⁻²d⁻¹) from white water Amazonian rivers (See Table 2 in the main manuscript). Therefore, the probability distributions adopted for the main channel emissions fluxes in this model rely on data from large natural rivers in the Amazon, which are

1 ACHANNEL = ARES - ABAYS
classified according to water type. These probability distributions are the same ones that we used
to estimate the emissions from the natural river in our TD-high RT model (natCO2 and natCH4).

Note, however, that the adoption of natural river flux data to represent the emissions from
the reservoir main channel is not the same of assuming low range of fluxes. Natural flux data
from Amazonian river shows that CH4 emissions rates can reach more than 600 mg CH4 m\textsuperscript{-2}d\textsuperscript{-1}
(Sawakuchi et al. 2014). Natural river emissions have average, maximum, and minimum values
with the same order of magnitude compared to surface reservoir emissions in the “old” Amazon
reservoirs (See Table 3 in the main document). The main difference between river and reservoir
fluxes in the Amazon is shape of the distributions. The natural river flux distributions are more
skewed to the right (longer right tail). See section Data Analysis for details.

With respect to stratified bays and tributaries zones, we assumed that fluxes in these areas
resemble the fluxes from stratified reservoirs (resCO2 and resCH4). Data from the Santo Antônio
reservoir also support this assumption (Fearnside 2015b). The reported flux for the tributary
zones (340 mg CH4 m\textsuperscript{-2}d\textsuperscript{-1}) is within the range adopted for resCH4 in the first year of operation (0
– 630 mg CH4 m\textsuperscript{-2}d\textsuperscript{-1}).

Compared to those of high RT reservoirs, degassing and downstream emissions in low
RT reservoirs are expected to be lower as the short RT and well-mixed conditions considerably
reduce CH4 concentrations in the water (DelSontro et al. 2010). Based on a single measurement
of the CH4 concentration in the air, a first order estimate from degassing and downstream
emissions from the Santo Antônio dam shows that these pathways correspond to 35% of the total
emissions in the first year of operation. Even though the measure was made at the peak of the
emission (first two years), this value is lower when compared to the degassing estimates in the
high RT reservoirs of Balbina (53% at age 18 (Kemenes, Forsberg & Melack 2007)), Petit Saut
(77% and 60% at age 9 and 10, respectively) and Tucuruí (88% at age 18) (Fearnside 2002). This result is expected because degassing/downstream emissions are positively correlated with CH$_4$ concentration in the reservoir (Abril et al. 2005; Guérin et al. 2006), which is then positively correlated with the RT (Galy-Lacaux et al. 1999; Delmas, Galy-Lacaux & Richard 2001).

Because only one degassing/downstream estimate is available for low RT reservoirs, we treated this variable parametrically in the TD-Low RT model. In other words, we did not fit a probability distribution for the degassing and downstream pathways. Instead, we treated the degassing/downstream fluxes as a single value based on the CH$_4$ value reported for the Santo Antônio reservoir (deg/down$\text{CH}_4$). Because of the high uncertainty (Fearnside 2015b), we present the results with and without the degassing/downstream estimates.

Based on the previously described assumptions, Equations S6 to S11 defines the mathematical formulation of the NRE for low RT reservoirs.

\[
\text{NRE}_{\text{lowRT}} = \text{Reservoir} + \text{Degassing/Downstream} - \text{Natural} \tag{S6}
\]

\[
\text{Reservoir} = \text{Emissions from the main channel} + \text{Emissions from bays/tributaries} \tag{S7}
\]

\[
\text{Emissions from main channel} = [(A_{\text{channel}} \times \text{natCO}_2) + (A_{\text{channel}} \times \text{natCH}_4)] \times 365 \tag{S8}
\]

\[
\text{Emissions from bays/tributaries} = [(A_{\text{channel}} \times \text{resCO}_2) + (A_{\text{channel}} \times \text{resCH}_4)] \times 365 \tag{S9}
\]

\[
\text{Degassing/Downstream} = (A_{\text{RES}} \times \text{deg/downCH}_4) \times 365 \tag{S10}
\]

\[
\text{Natural} = [(A_{\text{RIVERUP}} \times \text{resCO}_2) + (A_{\text{RIVERUP}} \times \text{resCH}_4)] \times 365 \tag{S11}
\]

Where $A_{\text{RIVERUP}}$ is the natural surface of the river, delimited by the beginning of the reservoir and the dam, and $A_{\text{RES}}$ is the reservoir area. Deg/down$\text{CH}_4$ corresponds to the degassing/downstream flux based on Santo Antônio reservoir. We presented the fluxes in
milligrams of the GHG gas per square meter per day (e.g. mg CH$_4$ m$^{-2}$ day$^{-2}$) and the surface areas in square kilometers.

We applied the same Monte Carlo simulation structure described to the high RT model to estimate the total emissions in a 100-years.

6.1.1.3 Densimetric Froude number and residence time

As previously described, we applied the TD models for new reservoirs located in the Brazilian Amazon. We selected 18 projects for model application from the Brazilian Energy Plans (MME EPE 2013; MME EPE 2014). To select the TD model that better represents each reservoir (high or low RT), we performed an analysis of the Densimetric Froude number and the RT. The Densimetric Froude, $F$, provides a measure of the success with which the horizontal flow can shift the thermal structure of the reservoir from that of its gravitational static-equilibrium state (EPA 1969; Straškraba, Tundisi & Duncan 1993; StrašKrab 1973). The $F$-number is representative of the main channel of the reservoirs. $F$-numbers greater than $1/\pi$ indicate that the main channel will not stratify and will behave like river zones. $F$-numbers around $1/\pi$ are representative of weakly stratified conditions. Reservoirs stratify when the $F$-number is lower than $1/\pi$ (EPA 1969). The $F$-number is defined by equation S12.

$$F = 0.32 \frac{(L/D)}{(Q/V)}$$  \hspace{1cm} (S12)

Where, $L$ is the reservoir length (km), $D$ is the average depth (m), $Q$ is the volumetric discharge calculated using the mean flow (m$^3$/s), and $V$ is the reservoir volume (hm$^3$).

The RT is also considered a reference value for reservoir stratification. Typical lake stratification occurs in reservoirs with high RT (>100 days) (StrašKrab 1973; Straškraba,
Reservoirs with low RT (<10 days), on the other hand, have a completely mixed water column, with a homogenous flow rate and temperature distribution (Straškraba 1973; Straškraba, Tundisi & Duncan 1993). Equation S13 defines RT.

\[
RT = \frac{V}{Q} \tag{S13}
\]

Where, RT is the residence time (seconds), V is the reservoir volume (m\(^3\)) and Q is the volumetric discharge calculated using the flow (m\(^3\)/s) in the period of analysis. To obtain the values in days, we divided equation S13 by the number of seconds in a day (60 x 60 x 24).

We calculated the RT and F-number for two monthly flow conditions using the historical monthly natural flows time series of each reservoir in our database: average flow scenario and an drought scenario defined as the flow equivalent to the 95% exceedance percentile in a flow duration curve (Q\(_{95\%}\)). Tables S1 and S2 describe the flow conditions for each reservoir in this study, while Tables S3-S6 described the densimetric Froude number and RT computations.

For the average flow scenario, Cachoeira do Caí and Jamanxim resulted in F-numbers lower than 1/\(\pi\) during the driest months (August to October) indicating that these reservoirs will stratify during this period. The RT is also high in the dry season and reaches average of 230 days in Cachoeira do Caí and 100 days in Jamanxim in the driest months (August to October). The Sinop reservoir also presents weak stratification conditions and high RT (~60 days) during the dry season (July to October). In the case of the Q\(_{95\%}\), the reservoirs of Cachoeira dos Patos and Ferreira Gomes also resulted in Froude numbers lower than 1/\(\pi\). The RT in this dry scenario is low in Ferreira Gomes (~15 days), but high in Cachoeira dos Patos (~200 days). The other reservoirs have high F-numbers and low RT throughout the year. Based on the characteristics of the reservoir operation, the RT and propensity to stratify, we suggest that the high RT model is representative of Cachoeira dos Patos, Cachoeira do Caí, Sinop, and Jamanxim reservoirs and the low RT model better represents the others reservoirs.
### Table S1 – Average Reservoir Flows (m$^3$/s)

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### Table S2 – Flow equivalent to the 95% exceedance percentile in a flow duration curve (m$^3$/s)

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Data not available to Marabá
### Table S3– Densimetric Froude (F)- Average flow scenario (m³/s)

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### Table S4– Densimetric Froude (F)- Q95% scenario (m³/s)

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Green: RT <30; Yellow: 30<RT<100; Red: RT>100

Table S6– Residence Time, RT (days) - Q95% scenario (m³/s)

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Green: RT <30; Yellow: 30<RT<100; Red: RT>100

6.1.2 Bottom-up approach

The BU approach consists of a mass balance to estimate net reservoir emission using

GHG production rates derived from incubation of soils and foliage from Petit Saut reservoir

(Guérin et al. 2008). The model has three modules:
1. The first module computes the emissions related to the below the ground C stock (flooded soils).

2. The second module accounts for the emissions related to the biomass in the vegetation that was not properly cleared and stays in the reservoir after flooding (flooded foliage).

3. The third module accounts for the emissions related to the vegetation that is cleared in the reservoir area.

The sum of the emissions computed in each module defines the net reservoir emissions in the bottom-up model. The model represents a lower bound estimate of emissions, as it does not account for OM imported or produced within the reservoir through primary production. We also applied a Monte Carlo simulation structure to estimate the net reservoir emissions. We repeated the simulation 10,000 times for each reservoir.

6.1.2.1 Module 1 – Emissions from flooded soils

The net reservoir emissions in this module are defined by the difference between production and consumption of GHG in the sediment surface/water column, taking into account CH$_4$ oxidation fraction (MOX) and bacteria growth efficiency (BGE).

The initial soil C stock is defined by the multiplication of the flooded area (discounted the natural river area) and the soil OM C density. We modeled the uncertainty of the below-the-ground C stock density by assuming a uniform distribution that varies from 8 to 16 Gg C km$^{-2}$ considering the 0-20cm layer (Cerri et al. 2007).

Equations S14 to S21 describe the mathematical formulation of the bottom-up model, which relies on monthly time steps to estimate emissions over 100 years:

$$\text{CH}_4 \text{ Production}_{\text{soils}} (t) = (\text{CH}_4 \text{ production Rate}_{\text{soils}}) \times \text{C Stock}_{\text{soils}} (t)$$

(S14)
\[
\text{CO}_2 \text{ Production}_{\text{soils}} \ (t) = (\text{CO}_2 \text{ production Rate}_{\text{soils}}) \times \text{ C Stock}_{\text{soils}} \ (t) \quad (S15)
\]
\[
\text{CH}_4 \text{ Consumption from CH}_4 \text{ oxidation} \ (t) = \text{CH}_4 \text{ Production} \ (t) \times (1 - \text{MOX}) \quad (S16)
\]
\[
\text{CO}_2 \text{ Production from CH}_4 \text{ oxidation} \ (t) = \text{CH}_4 \text{ Production} \ (t) \times (\text{MOX}) \times \text{BGE} \quad (S17)
\]
\[
\text{CH}_4 \text{ Emission}_{\text{soils}} \ (t) = \text{CH}_4 \text{ Production}_{\text{soils}} \ (t) - \text{CH}_4 \text{ Consumption from CH}_4 \text{ oxidation} \ (t) \quad (S18)
\]
\[
\text{CO}_2 \text{ Emission}_{\text{soils}} \ (t) = \text{CO}_2 \text{ Production}_{\text{soils}} \ (t) + \text{CO}_2 \text{ Production from CH}_4 \text{ oxidation} \ (t) \quad (S19)
\]
\[
\text{NRE}_{\text{soils}} \ (t) = \text{CH}_4 \text{ Emission}_{\text{soils}} \ (t) + \text{CO}_2 \text{ Emission}_{\text{soils}} \ (t) \quad (S20)
\]
\[
\text{C Stock}_{\text{soils}} \ (t+1) = \text{C Stock}_{\text{soils}} \ (t) - \text{CH}_4/\text{CO}_2 \text{ Production}_{\text{soils}} \ (t) \quad (S21)
\]

A normal distribution defines the C production rates in this model. This probability distribution relies on the average and standard deviation of GHG potential production rates obtained from incubation of soils from Petit Saut reservoir (260 ± 56 nmol (CH\textsubscript{4}) g\textsuperscript{-1} h\textsuperscript{-1} and 350 ± 69 nmol (CO\textsubscript{2}) g\textsuperscript{-1} h\textsuperscript{-1}). We assumed that production rates are the same for stratified and well mixed water column reservoirs, because soil saturation leads to anaerobic decomposition at this layer in both conditions (Davidson & Janssens 2006).

**Methane Oxidation Fraction (MOX)**

The aerobic methane-oxidizing bacteria consume part of the CH\textsubscript{4} produced by methanogenesis. The literature shows that CH\textsubscript{4} oxidation is a very efficient process in reducing CH\textsubscript{4} outgas to the atmosphere in freshwater environments (Bastviken 2009; Angelis & Scranton 1993; Guérin & Abril 2007; Kemenes, Forsberg & Melack 2007). CH\textsubscript{4} oxidation may occur in the sediment surface, as well as the water column, and it is positively correlated with CH\textsubscript{4} concentration, temperature, and availability of O\textsubscript{2} (Bastviken 2009). Our BU model requires an estimate of the fraction of the CH\textsubscript{4} produced that is oxidized before reaching the atmosphere (variable MOX).

CH\textsubscript{4} oxidation in stratified tropical reservoirs happens in both the reservoir and in the river below the dam (Guérin & Abril 2007; Kemenes, Forsberg & Melack 2007). In stratified
water bodies, CH$_4$ oxidation occurs within the thermocline between the aerobic epilimnion and the anoxic and methane-saturated hypolimnion (Guérin & Abril 2007; Hanson & Hanson 1996). Below the dam, the reduction of CH$_4$ concentration with distance in the rivers is attributed to gas evasion and CH$_4$ oxidation (Guérin et al. 2006). In Petit Saut, about 90% of the CH$_4$ reaching the hypolimnion was oxidized in the reservoir or downstream (Guérin et al. 2006). In Balbina, 85% of the CH$_4$ loss downstream the dam was attributed to CH$_4$ oxidation (Kemenes, Forsberg & Melack 2007).

MOX data in reservoirs with well-mixed water column (low RT) are not available for Amazon reservoirs. The only measure for a low RT reservoir was made in Lake Wohlen, Switzerland, where the oxidation in water column was found to be negligible (DelSontro et al. 2010). However, the measurements made in Switzerland do not assess the oxidation in the sediment surface. In the case of methanogenic sediments overlain with oxic water in river and lakes, methanotrophic bacteria occur at the top of sediments, as well as in the water column (Hanson & Hanson 1996; Bastviken 2009; Angelis & Scranton 1993). A meta-analysis of CH$_4$ oxidation fractions in oxic lakes shows that 50% to 95% of the produced CH$_4$ is oxidized above the sediment (Bastviken 2009). In the case CH$_4$ oxidation in the water column, the data from lakes show that CH$_4$ oxidation fraction varies from 45% to 100% and that it is highly dependent on the mixing regime and depth (Bastviken 2009). With respect to rivers, a C balance for the Hudson River, United States, indicates that CH$_4$ oxidation in the water column removes from 13% to 70% of the produced CH$_4$ (Angelis & Scranton 1993).

The literature shows that MOX in different water column conditions vary significantly but overlap. As a result, we did not distinguish between high and low RT reservoirs in this
approach. Instead, we assumed the same MOX for both water column conditions, which is defined by uniform distribution between 45% and 95%.

$\text{CH}_4$ oxidation results in $\text{CO}_2$ production, and we assume that the BGE (required in Equation S17) has a triangular distribution that ranges from 10% to 80% (Bastviken et al. 2003) and has the most probable value at 50% (Guérin et al. 2008).

6.1.2.2 Module 2 – Emissions from flooded foliage

Currently, the Brazilian environmental rules for reservoir construction specify the need to implement vegetation-clearing programs in the reservoir areas to reduce the hazardous effect of biomass decomposition in the water quality (Tundisi & Rocha 1998). However, the enforcement of this rule has been neglected in the past, such as the Teles Pires reservoir (CHTP 2015).

To address the issue of incomplete vegetation clearing in some reservoirs, we included a second degradation module. This module follows the same structure adopted to estimate emissions from soils (Guérin et al. 2008). The multiplication of the flooded area (discounting the natural river area) and C density of foliage (leaves and branches) defines the C stock. C densities of leaves and branches are assumed to be 0.6 Gg C km$^{-2}$ and 5.8 Gg C km$^{-2}$, respectively (Malhi, Baldocchi & G 1999). Based on these values, we adopted a uniform distribution between 0.6 (only leaves) and 6.4 (sum of leaves and branches) Gg C/km$^2$ to represent the uncertainty in the C density of foliage that may remain in the reservoir. The net reservoir emissions from flooded foliage are defined as the difference between GHG production and consumption in the water column, taking into account MOX and BGE.

$$\text{CH}_4 \text{ Production}_{\text{foliage}} \ (t) = (\text{CH}_4 \text{ production Rate}_{\text{foliage}}) \ast \text{ C Stock}_{\text{foliage}} \ (t) \quad \text{(S22)}$$
$\text{CO}_2 \text{ Production}_{\text{foliage}} (t) = (\text{CO}_2 \text{ production Rate}) \times \text{C Stock}_{\text{foliage}} (t)$  

(S23)

$\text{CH}_4 \text{ Consumption from CH}_4 \text{ oxidation} (t) = \text{CH}_4 \text{ Production}_{\text{foliage}} (t) \times (1 - \text{MOX})$  

(S24)

$\text{CO}_2 \text{ Production from CH}_4 \text{ oxidation} (t) = \text{CH}_4 \text{ Production}_{\text{foliage}} (t) \times (\text{MOX}) \times \text{BG}$  

(S25)

$\text{CH}_4 \text{ Emissions}_{\text{foliage}} (t) = \text{CH}_4 \text{ Production}_{\text{foliage}} (t) - \text{CH}_4 \text{ Consumption from CH}_4 \text{ oxidation} (t)$  

(S26)

$\text{CO}_2 \text{ Emissions}_{\text{foliage}} (t) = \text{CO}_2 \text{ Production}_{\text{foliage}} (t) + \text{CO}_2 \text{ Production from CH}_4 \text{ oxidation} (t)$  

(S27)

$\text{NRE}_{\text{foliage}} (t) = \text{CH}_4 \text{ Emissions} (t) + \text{CO}_2 \text{ Emissions} (t)$  

(S28)

$\text{C Stock}_{\text{foliage}} (t+1) = \text{C Stock}_{\text{foliage}} (t) - \text{CH}_4/\text{CO}_2 \text{ Production}_{\text{foliage}} (t)$  

(S29)

A lognormal distribution defines the C production rates in this module. This probability distribution relies on the average and standard deviation of GHG potential production rates obtained from incubation of foliage from Petit Saut reservoir (2400 ± 1000 mmol (CH$_4$) g$^{-1}$h$^{-1}$ and 3900 ± 5000 nmol (CO$_2$) g$^{-1}$h$^{-1}$) (Guérin et al. 2008).

MOX and BGE follow the same assumptions described for the Module 1– Emissions from flooded soils.

6.1.2.3 Module 3 – Emissions from the cleared vegetation

This module computes the GHG emissions related to C stock contained in the removed biomass from the reservoir area. As previously mentioned, Brazilian environmental rules require vegetation clearing of the flooded area before filling the reservoir (Kubistcheck 1960). Based on spatial information of the biomass density within each reservoir, we estimated the emissions related to the vegetation clearing for each reservoir according to the equation S30.

$\text{NRE}_{\text{biomass}} = \text{Biomass density} \times (A_{\text{RES}} - A_{\text{RIVERUP}}) \times \text{C content}$  

(S30)
Where, Biomass density is defined by uniform distribution with maximum and minimum values described in Table S7. C content is the proportion of C in the biomass, which is assumed to be 50% (Martin & Thomas 2011; Feldpausch & Rondon 2004).

Table S7 – Biomass density range from the studied reservoirs (Gg km$^{-2}$). See section for the method to define the minimum and maximum values.

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<th>Min (Gg km$^{-2}$)</th>
<th>Max (Gg km$^{-2}$)</th>
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<tr>
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</table>

The biomass map (Saatchi et al. 2007), which is the base for the biomass density calculation, is calibrated using forest monitoring plots. Forest monitoring plots range from 0.5–50 ha in area, and within them, every individual tree over a certain threshold size (usually $\geq$100 mm diameter-at-breast-height) is identified, measured, and monitored over time (Lewis et al. 2009). Given the uncertainty related to the quality of the plots (Saatchi et al. 2007) and the limitation of these studies to account for the C below a certain threshold, we assumed that this C pool is independent of our estimates for foliage described in Module 2.

The fate of the C from vegetation clearing is variable and uncertain. According to Teles Pires reservoir vegetation clearing report (CHTP 2015), large trunks were used in the
construction industry. Regarding smaller trunks and branches, the material was used to make charcoal and firewood. The small residues and vegetation were buried in the shallow excavations in the ground; a similar procedure was also applied in the Santo Antônio (Fearnside 2015b). We assumed that the C from the cleared biomass is released into the atmosphere, as CO$_2$, within a period of 30 years.

6.2 Data from new hydroelectric power plants in the Amazon

Data about the hydroelectric plants in this study came from the Brazilian Electric Agency (Agencia Nacional de Energia Elétrica – ANEEL). These data came from river basin hydroelectric Master plans, known as “estudos de inventario hidrelétrico”, and viability studies approved by ANEEL. The studies are public and provided by ANEEL. We selected 18 projects for model application from the Brazilian Energy Plans (MMEEPE 2010; EPEMME 2012). Figure S2 shows the spatial location of the studied reservoirs. Table 2-1 (Chapter 2) describes the characteristics of the studied reservoirs. Table S8 shows the ANEEL process number. The process number is the study reference identification in the agency and can be used to request the data.
Figure S2 - Spatial distribution of the studied reservoirs
### Table S8 - Information about the hydroelectric studies approved by ANEEL and used in this study.

<table>
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<td>Master plan</td>
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<td>Viability</td>
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<td>48500.003933/2006-77</td>
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<td>Ferreira Gomes</td>
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<tr>
<td>São Manoel</td>
<td>48500.004789/2006-78</td>
<td>Viability</td>
</tr>
<tr>
<td>São Simão Alto</td>
<td>48500.001701/2006-11</td>
<td>Master plan</td>
</tr>
<tr>
<td>Sinop</td>
<td>48500.004784/2006-54</td>
<td>Viability</td>
</tr>
<tr>
<td>Teles Pires</td>
<td>48500.004785/2006-17</td>
<td>Viability</td>
</tr>
</tbody>
</table>

The model inputs include two sets of variables, one related to landscape characteristics of the river/reservoir and another related to the flux rates per area per time. The variables related to the river/reservoirs, which we consider to be defined constants, include reservoir area ($A_{RES}$), the area of bays and tributary ($A_{BAYS}$), and natural river surface areas within the model boundaries ($A_{RIVERDOWN}$ and $A_{RIVERUP}$). Table S9 summarizes these data, which came from design documents cross-referenced to remote sense data using GIS techniques (See section 2.1 for details about the method to obtain the surface areas).
Table S9 – Surface area of rivers and reservoirs defined by the model boundaries and used as inputs for the models.

<table>
<thead>
<tr>
<th>Hydroelectric Power Plant Name</th>
<th>River</th>
<th>Reservoir Area: $A_{res}$ (km$^2$)</th>
<th>River Downstream Area: $A_{RIVERDOWN}$ (km$^2$)</th>
<th>River Area: $A_{RIVER}$ (km$^2$)</th>
<th>River Area upstream: $A_{RIVERUP}$ (km$^2$)</th>
<th>Bays/ Tributary Area ($A_{BAYS}$)</th>
<th>Reservoir length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belo Monte</td>
<td>Xingu</td>
<td>516</td>
<td>245</td>
<td>484</td>
<td>239</td>
<td>28</td>
<td>89</td>
</tr>
<tr>
<td>Bem Querer</td>
<td>Branco</td>
<td>559</td>
<td>39</td>
<td>155</td>
<td>116</td>
<td>104</td>
<td>146</td>
</tr>
<tr>
<td>Cachoeira do Caí</td>
<td>Jamanxim</td>
<td>420</td>
<td>18</td>
<td>57</td>
<td>39</td>
<td>n/a</td>
<td>144</td>
</tr>
<tr>
<td>Cachoeira do Caldeirão</td>
<td>Araguari</td>
<td>48</td>
<td>32</td>
<td>48</td>
<td>16</td>
<td>11</td>
<td>52</td>
</tr>
<tr>
<td>Cachoeira dos Patos</td>
<td>Jamanxim</td>
<td>117</td>
<td>11</td>
<td>26</td>
<td>15</td>
<td>n/a</td>
<td>68</td>
</tr>
<tr>
<td>Colider</td>
<td>Teles Pires</td>
<td>172</td>
<td>11</td>
<td>37</td>
<td>26</td>
<td>54</td>
<td>98</td>
</tr>
<tr>
<td>Ferreira Gomes</td>
<td>Araguari</td>
<td>18</td>
<td>20</td>
<td>26</td>
<td>6</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Jamanxim</td>
<td>Jamanxim</td>
<td>74</td>
<td>13</td>
<td>19</td>
<td>6</td>
<td>n/a</td>
<td>44</td>
</tr>
<tr>
<td>Jatobá</td>
<td>Tapajós</td>
<td>646</td>
<td>106</td>
<td>474</td>
<td>368</td>
<td>173</td>
<td>132</td>
</tr>
<tr>
<td>Jirau</td>
<td>Madeira</td>
<td>303</td>
<td>53</td>
<td>124</td>
<td>71</td>
<td>97</td>
<td>140</td>
</tr>
<tr>
<td>Marabá</td>
<td>Tocantins</td>
<td>1,024</td>
<td>70</td>
<td>403</td>
<td>333</td>
<td>122</td>
<td>202</td>
</tr>
<tr>
<td>Salto Augusto de Baixo</td>
<td>Juruena</td>
<td>125</td>
<td>52</td>
<td>96</td>
<td>44</td>
<td>38</td>
<td>49</td>
</tr>
<tr>
<td>Santo Antônio</td>
<td>Madeira</td>
<td>271</td>
<td>44</td>
<td>140</td>
<td>96</td>
<td>66</td>
<td>134</td>
</tr>
<tr>
<td>São Luís do Tapajos</td>
<td>Tapajós</td>
<td>722</td>
<td>74</td>
<td>399</td>
<td>325</td>
<td>212</td>
<td>123</td>
</tr>
<tr>
<td>São Manoel</td>
<td>Teles Pires</td>
<td>64</td>
<td>34</td>
<td>44</td>
<td>10</td>
<td>17</td>
<td>45</td>
</tr>
<tr>
<td>São Simão Alto</td>
<td>Juruena</td>
<td>284</td>
<td>35</td>
<td>83</td>
<td>48</td>
<td>114</td>
<td>120</td>
</tr>
<tr>
<td>Sinop</td>
<td>Teles Pires</td>
<td>330</td>
<td>13</td>
<td>33</td>
<td>20</td>
<td>n/a</td>
<td>122</td>
</tr>
<tr>
<td>Teles Pires</td>
<td>Teles Pires</td>
<td>152</td>
<td>19</td>
<td>47</td>
<td>28</td>
<td>51</td>
<td>65</td>
</tr>
</tbody>
</table>

n/a: not applied because high residence time reservoir are not divided in zones (main channel and tributary/bays).

We also compute the emission factor of each hydropower plant, based on the capacity factor and installed capacity described in Table 2-1 (Chapter 2) and according to the equation below:

$$\text{Emission factor} = \frac{(\text{NRE})}{(\text{number of years}*\text{Power} \times \text{Capacity Factor} \times 365 \text{ days} \times 24 \text{ hours})}$$  \hspace{1cm} (S31)

Where NRE is the net GHG reservoir emissions, in CO$_2$eq, estimated through the statistical models. Power is the installed capacity in MW. The emission factor (g CO$_2$eq MWh$^{-1}$).
is an important parameter in evaluating the service provided by hydroelectric reservoir in comparison to other sources of electricity (Ometto et al. 2013). The scope and boundary of this study excludes emissions from construction of the physical infrastructure. Furthermore, the emissions factors reported for the different generating assets rely on net output at the power plant gate and do not include power losses associated with the long-distance transmission system.

6.2.1 Surface areas analysis

This section provides detailed information about the method employed to estimate the surface areas, which are inputs for our models. These surface areas include the reservoir area \( A_{\text{RES}} \), the natural river areas \( A_{\text{RIVER}}, A_{\text{RIVERUP}} \) and \( A_{\text{RIVERDOWN}} \) and bays/tributary areas \( A_{\text{BAYS}} \).

First, we imported computer-aided design (CAD) files \( .dwf \) file extension) containing the shape of the reservoirs to a shapefile \( .shp \) file extension) using the software ArcGis. The CAD files are part of the design documents obtained from ANEEL. Figure S3 shows an example of this importing procedure for the Colíder reservoir. The reservoir area \( A_{\text{RES}} \) corresponds to the total reservoir area estimated using the imported polygon for each reservoir.
In the case of run-of-river reservoirs, the reservoir water level does not suffer significant water level variation throughout the year. Therefore, the reservoir shape corresponds to the normal level of operation.

In the case of storage reservoirs, however, the definition of the reservoir area is a source of uncertainty because the variation of the water level can be significant. Table S10 presents the characteristics of the storage reservoirs. The data in Table S10 shows that the reservoirs of Cachoeira do Caí, Cachoeira dos Patos, and Sinop have a significant variation of the reservoir area.
Our baseline calculations assume $A_{\text{RES}}$ at the maximum normal level for storage reservoir. To address effect of the variation of the area for storage reservoirs in our estimates, we performed a sensitivity analysis for these three reservoirs using the area ($A_{\text{RES}}$) at the normal level as new values in the simulations.

Table S10 – Storage reservoirs characteristics: operational water levels, volume and areas.

<table>
<thead>
<tr>
<th>Project</th>
<th>Water Levels</th>
<th>Volume (hm$^3$)</th>
<th>Reservoir Area (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal Maximum</td>
<td>Normal Minimum</td>
<td>Normal (average)</td>
</tr>
<tr>
<td>São Luiz do Tapajós</td>
<td>50.0</td>
<td>49.6</td>
<td>49.8</td>
</tr>
<tr>
<td>Cachoeira do Caí</td>
<td>85.0</td>
<td>82.9</td>
<td>83.8</td>
</tr>
<tr>
<td>Jamanxim</td>
<td>143.0</td>
<td>142.2</td>
<td>142.5</td>
</tr>
<tr>
<td>Cachoeira dos Patos</td>
<td>176.0</td>
<td>173.1</td>
<td>174.3</td>
</tr>
<tr>
<td>Sinop</td>
<td>302.0</td>
<td>292.0</td>
<td>297.0</td>
</tr>
</tbody>
</table>

Second, we used the *shapefile* of the reservoir surface to clip a raster image containing the information about surface lands and water. This raster image defines global land surface and permanent water bodies based on Landsat 8 satellite data from 2000 to 2013 (Hansen et al. 2013). The image spatial resolution is 30 meters. Figure S4 shows an example of the result of this procedure. Based on these data and method, we defined the natural river surface within the reservoir area ($A_{\text{RIVERUP}}$), which corresponds to the blue area (permanent water bodies). We applied the same data and procedure to calculate the natural river area downstream the dam ($A_{\text{RIVERDOWN}}$). The only difference is that we clip the raster image containing the permanent water body using the dam as an upper bound, and 40-km distance downstream the dam as the lower bound.
Third, we divided the total reservoir area in two groups: bays and tributaries, and main water body (main channel). This information is used to calculate the low RT reservoir emission in the TD approach. Low RT reservoirs have a well-mixed water column in the main reservoir water body, but stratified conditions in the bays and tributaries zones. Figure S5 shows an example of this division for Colíder reservoir.

Figure S4 – *A_{RIVERUP} determination example for Colíder reservoir.*

Legend

- **Land Surface**
- **Permanent water bodies**

Data Source:
- Land/Water surface Hansen, 2013
- Reservoir shape: viability study - ANEEL
6.2.2 Above the ground biomass density in the reservoir area

The above the ground biomass density in the reservoir area is an input to calculate the above the ground C stock in the BU model (module 3). We calculated the amount of biomass in the reservoir using a similar procedure described to obtain the natural river areas. The data source is a raster file containing the Amazon basin aboveground live biomass spatial distribution (Saatchi et al. 2008). This raster image contains forest biomass density (in Mg ha\(^{-1}\)) divided among 11 classes at 1 km spatial resolution. Remote sensing and ground data used to produce
these data were collected from 1990 to 2000. To estimate the total biomass in the reservoir area, we cut the raster image using the reservoir shape as illustrated in Figure S6.

Figure S6 – Above the ground biomass determination example for Colider reservoir. Legend values are in Mg ha\(^{-1}\).

The result of the procedure is a table containing the number of pixels for each C density class within the reservoir area. Table S11 presents an example of this table to Colider reservoir.
Table S11 – Biomass density estimation intermediary results: Colíder reservoir example.

<table>
<thead>
<tr>
<th>Class</th>
<th>Biomass Density Range (Mg km$^{-2}$)</th>
<th>Number of pixels per class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-0.25</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>0.25-0.50</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>0.50-0.75</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>0.75-1.00</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>1.00-1.50</td>
<td>85</td>
</tr>
<tr>
<td>6</td>
<td>1.50-2.00</td>
<td>70</td>
</tr>
<tr>
<td>7</td>
<td>2.00-2.50</td>
<td>22</td>
</tr>
<tr>
<td>8</td>
<td>2.50-3.00</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>3.00-3.50</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>3.50-4.00</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>&gt;4.00</td>
<td>0</td>
</tr>
</tbody>
</table>

Total number of pixels (1 pixel = 1 km$^2$) = 281

Note that spatial resolution of the data generates an uncertainty when a pixel is not completely inside the reservoir shape. The GIS software algorithms integrate this pixel as part of the calculation resulting in a greater area compared to the area of the reservoir shape. For the Colíder example in Table S11, the total area is 281 km$^2$, while the correct reservoir area is 172 km$^2$. Thus, the estimation of the above the ground biomass using the total number of pixels would lead to an overestimation of the available biomass. To overcome this issue, we used the following procedure to define the minimum and maximum C density values for each reservoir:

1. We estimated a maximum value for the total above the ground biomass in the reservoir area by multiplying the maximum range from each class (e.g., Class 1 equals 0.25 Mg km$^{-2}$ in Table S11) by the number of pixels (e.g., Class 1 equals 20 in Table S11), and summing these values across all classes.

2. We estimate a minimum value for the total above the ground biomass in the reservoir area by multiplying the minimum range from each class (e.g., Class 1 equals 0 Mg km$^{-2}$ in Table S11) by the number of pixels, and summing these values across all classes.
3. We divided the maximum and minimum total mass values (results from step 1 and 2) by the total number of pixels obtaining a range for the above the ground biomass density in the reservoir area.

4. The maximum and minimum biomass density values are used as inputs to define the uncertainty of Equation S30.

The biomass density range results for each reservoir are presented in Table S7.

6.3 Data Analysis - Top-down approach

The TD model defines the flux rates (res$_{CO_2}$, res$_{CH_4}$, deg$_{CO_2}$, deg$_{CH_4}$, down$_{CO_2}$, down$_{CH_4}$, nat$_{CO_2}$ and nat$_{CH_4}$) by probability distributions that were fitted using published data from Amazon water bodies. The following paragraphs describe the data used to build TD approach. We fit several continuous distributions (Beta, Exponential, Extreme value, Gamma, Generalized extreme value, Generalized Pareto, Inverse Gaussian, Logistic, Log-logistic, Lognormal, Normal, Rayleigh and Weibull) to the data using MATLAB and its function allfitdist (Sheppard 2012). The MATLAB function fits most distributions using maximum likelihood estimation. We chose the best distribution through the calculation of the Bayesian Information Criterion (BIC) and Akaike Information Criterion (AIC), which are penalized criteria statistics for model selection. The sum of two terms characterizes the BIC and AIC. The first term is the difference of the maximized log-likelihoods and reflects the fit of the model to the observational data. The second term measures the complexity of the model and thus serves as a penalty for more complex models (Kuha 2004).
6.3.1 Natural River Emissions (nat\textsubscript{CO2} and nat\textsubscript{CH4})

We collected published data of CO\textsubscript{2} (Rasera et al. 2008; 2013; Ellis, Richey, Aufdenkampe, et al. 2012; Alin et al. 2011; Salimon et al. 2012) and CH\textsubscript{4} (Sawakuchi et al. 2014) fluxes in Amazon rivers (>100m) classifying the measurements by water-chemistry type. We selected a total of 184 and 453 data points for CO\textsubscript{2} and CH\textsubscript{4} flux rates, respectively. Data from Alin et al. (2011) and Ellis et al. (2012) are available for download from Oak Ridge National Laboratory Distributed Active Archive Center (Alin & Richey 2012; Ellis, Richey, Krusche, et al. 2012). Our database only includes measurements made on large rivers, because all the new power plants evaluated in this study are located in large rivers. The database is available upon request.

In the case of CO\textsubscript{2}, the data points can be divided in two groups. The first group consists of data points where the reported values in the papers are averages from multiple measurements. The second group contains not only the averages, but also the raw data (individual field measurements). In other words, the second group contains independent measurements before any statistical treatment. To standardize the database, we calculated the average fluxes for measurements sampled on the same day and site (raw data), resulting in 95 data points for CO\textsubscript{2} fluxes. We used the database to fit distributions for the natural river flux rates according to the water chemistry type. Optical characteristics are the basis of the water type classification: black water is associated with a high content of humic compounds; white water is associated with a high content of suspended sediment; and clear water is characterized by the lack of turbidity caused by sediments and a dark color caused by humic compounds (Furch 1984; Junk et al. 2011).
Alin et. al (2011) studied the physical controls on CO₂ flux in low-gradient systems in the Amazon and Mekong river systems. CO₂ fluxes varied from 0.04 (150 mg CO₂ m⁻² d⁻¹) to 14.2 mmol m⁻² s⁻¹ (54,000 mg CO₂ m⁻² d⁻¹) in large rivers and from 0.7 (2661 mg CO₂ m⁻² d⁻¹) to 12.4 mmol m⁻² s⁻¹ (47,000 mg CO₂ m⁻² d⁻¹) in small rivers. They concluded that wind speed is the main physical control on gas exchange in estuaries and large rivers, while water current velocity and water depth become the drivers of these fluxes as the river size decreases (Alin et al. 2011).

Rasera et. al (2008) evaluated the factors controlling water-column respiration in small rivers of the central and southwestern Amazon basin. They reported CO₂ outgassing rates varying from 1 mmol C m⁻² s⁻¹ (3,800 mg CO₂ m⁻² d⁻¹) to 12.7 mmol C m⁻² s⁻¹ (48,000 mg CO₂ m⁻² d⁻¹). According to the authors, most rivers showed similar seasonal patterns, with CO₂ outgassing increasing during a high water period when compared to those observed at low water. Because this work focused on small rivers (width <100m), the selected data points from this reference come only from Ji-Paraná River (Rasera et al. 2008).

Rasera et. al (2013) assessed the spatial and temporal variability of CO₂ efflux in seven Amazonian Rivers and found rates varying from -0.8 (-3,000 mg CO₂ m⁻² d⁻¹) to 15.3 (58,000 mg CO₂ m⁻² d⁻¹). Negative fluxes were reported in Araguaia, Javaes and Teles Pires during dry season, indicating that the role of photosynthesis in fluvial systems of the Amazon should be better understood in estimates of the basin’s C balance. The authors concluded that CO₂ flux variability is modulated by the seasonal cycle of CO₂ partial pressure (pCO₃), which is highly correlated with the water flow variability (Rasera et al. 2013).

Natural CH₄ emissions from rivers in the Amazon also exhibit significant spatial and temporal variability related to the water type, river morphology, and season. Average fluxes
across measured Amazonian rivers range from 0.04 to 6.0 mmol CH$_4$ m$^{-2}$ d$^{-1}$ (6.4 to 96 mg CH$_4$ m$^{-2}$ d$^{-1}$) (Sawakuchi et al. 2014).

Table S12 presents the summary of the statistics for each dataset. Figures S7, S8 and S9 show the histograms and adjusted distribution for CO$_2$ and CH$_4$ by water type.

<table>
<thead>
<tr>
<th>Water Type</th>
<th>CH$_4$</th>
<th>CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>White</td>
<td>Black</td>
</tr>
<tr>
<td>Average</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>Stand. Dev.</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>Min.</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Max.</td>
<td>160</td>
<td>54</td>
</tr>
<tr>
<td>Skew</td>
<td>4.0</td>
<td>2.6</td>
</tr>
<tr>
<td>n</td>
<td>214</td>
<td>73</td>
</tr>
</tbody>
</table>

Figure S7 - Black water CH$_4$ and CO$_2$ flux data histograms and fitted distributions. CH$_4$ Black Water: Inverse Gaussian (mean ($\mu$)= 7.18, shape ($\lambda$)=3.88); CO$_2$ Black Water: Rayleigh Distribution (scale (b)=1.7862e+04).
Figure S8 - Clear water CH$_4$ and CO$_2$ flux data histograms and fitted distributions. CH$_4$ Clear Water: Inverse Gaussian (mean ($\mu$) = 72.95, shape ($\lambda$) = 10.81). CO$_2$ Clear Water: Generalized Extreme Value distribution (shape ($k$) = 0.2964; Location ($\mu$) = 2.8263e+03; scale ($\sigma$) = 3.3465e+03).

Figure S9 - White water CH$_4$ and CO$_2$ flux data histograms and fitted distributions. CH$_4$ white water: Generalized Pareto (shape ($k$) = 0.6947; scale ($\sigma$) = 4.4007; thresholds ($\theta$) = 0.0899). CO$_2$ white water: Rayleigh Distribution (scale ($b$) = 1.6336e+04).
6.3.2 Ebbulitive and diffusive emissions from the reservoir (res\(\text{CO}_2\) and res\(\text{CH}_4\))

The reservoir surface emits \(\text{CO}_2\) and \(\text{CH}_4\) through ebullition and diffusion. The anaerobic decomposition of the OM present in the reservoir sediments produces \(\text{CH}_4\), which is released from the sediments as bubbles because of its low solubility (Demarty & Bastien 2011). Diffusion is the flux that occurs in the air-water interface because of the difference in gas concentration at this layer (Demarty & Bastien 2011).

We selected data from four old forested tropical reservoirs (Balbina, Tucuruí, Samuel and Petit Saut) to fit the probability distributions that describe the reservoir surface fluxes in the TD approach (Abril et al. 2005; Guérin et al. 2006; Kemenes, Forsberg & Melack 2007; 2011; Santos et al. 2006; Lima 2005; Fearnside 2002). Table S13 details the characteristics of these reservoirs. We collected 15 data points for \(\text{CO}_2\) diffusion and 20 data points for \(\text{CH}_4\) fluxes (diffusion plus ebullition), which are described in Table S14.

Table S13 - Reservoirs Characteristics (Old Reservoirs).

<table>
<thead>
<tr>
<th>Hydroelectric Power Plant Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Power (MW)</th>
<th>Reservoir Area: (A_{\text{res}}) (km(^2))</th>
<th>Reservoir Volume (x10(^{6}) m(^3))</th>
<th>Mean Flow (m(^3)/s)</th>
<th>Residence Time (days)</th>
<th>Energy Density (MW/km(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tucurui</td>
<td>-3.834</td>
<td>-49.648</td>
<td>8370</td>
<td>2875</td>
<td>45500</td>
<td>11000</td>
<td>48</td>
<td>2.91</td>
</tr>
<tr>
<td>Samuel</td>
<td>-8.751</td>
<td>-63.457</td>
<td>216</td>
<td>560</td>
<td>3490</td>
<td>350</td>
<td>115</td>
<td>0.39</td>
</tr>
<tr>
<td>Balbina</td>
<td>-1.917</td>
<td>-59.481</td>
<td>250</td>
<td>2360</td>
<td>17500</td>
<td>577</td>
<td>351</td>
<td>0.11</td>
</tr>
<tr>
<td>Petit Saut</td>
<td>5.063</td>
<td>-53.048</td>
<td>116</td>
<td>310</td>
<td>3500</td>
<td>267</td>
<td>152</td>
<td>0.37</td>
</tr>
</tbody>
</table>

NOTE: We recalculated the annual residence time for the Tucurui reservoir with the objective to standardize the calculation method with the other reservoirs. We estimated the annual average residence time by dividing volume and average annual flow. The average annual residence time provided in (Fearnside 2002) is 96, which is a result of the average of monthly residence time values (calculated with monthly flows).

Data from Petit Saut, where emissions have been measured since the impoundment in 1993 (Galy-Lacaux et al. 1999; Delmas et al. 2005; Abril et al. 2005), suggest that \(\text{CO}_2\) diffusive and \(\text{CH}_4\) diffusive and bubbling emissions stabilized 7 years and 4 years after the impoundment, respectively (Abril et al. 2005). For Petit Saut, we only included measurements after
stabilization. The data points from the Balbina, Tucuruí, and Samuel reservoirs were sampled at least 9 years after the impoundment. We assumed that all these fluxes represent steady state conditions. (Kemenes, Forsberg & Melack 2007; 2011; Guérin et al. 2006; Lima 2005; Santos et al. 2006).

Average CO$_2$ emissions variability is high and range from 1,500 to 43,000 mg CO$_2$ m$^{-2}$d$^{-1}$. One data point for Samuel is responsible for the large upper bound. Without this extreme point, CO$_2$ emissions range from 1,500 to 14,000 mg CO$_2$ m$^{-2}$d$^{-1}$. The average value of the CO$_2$ flux reported in Samuel reservoir after 16 years of the impoundment (Guérin et al. 2006) is around three times higher than the second highest CO$_2$ emissions (found in Balbina). Exceptional weather conditions during the flux measurement campaign explain this high value (Guérin et al. 2006), which cannot be used to represent long-term average conditions. Additionally, a box plot analysis of the data indicates that this point is a statistical outlier. The physical conditions of the measurement and the statistical analysis indicate that this point is a potential outlier. As a consequence, our baseline calculations do not take this point into account. However, we present a sensitivity analysis of the simulation results considering this point latter in this Appendix.

With respect to CH$_4$, the reported fluxes variability is also high. Average CH$_4$ fluxes vary from 1 to 205 mg CH$_4$ m$^{-2}$d$^{-1}$. CH$_4$ fluxes include both diffusion and ebullition. Table S14 describes selected CO$_2$ diffusion (res$_{CO2}$) and CH$_4$ ebullition plus diffusion (res$_{CH4}$) fluxes, and Figure S10 shows the adjusted probability distributions.
Table S14 - Diffusion and ebullition emission fluxes measured in tropical forested reservoirs. Values in the brackets represent the reported standard deviation or range.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Reservoir Area (km²)</th>
<th>Age when Sampled</th>
<th>**Diffusion CO₂ (mg CO₂.m⁻².day⁻¹)</th>
<th>Diffusion CH₄ (mg CH₄.m⁻².day⁻¹)</th>
<th>Ebulition CH₄ (mg CH₄.m⁻².day⁻¹)</th>
<th>Diffusion + ebullition CH₄ (mg CH₄.m⁻².day⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petit Saut</td>
<td>7</td>
<td>4</td>
<td>12</td>
<td>6</td>
<td>19</td>
<td>123.2 (140.8)</td>
<td>Abril et al 2005</td>
</tr>
<tr>
<td>Petit Saut</td>
<td>300</td>
<td>5</td>
<td>28</td>
<td>5</td>
<td>34</td>
<td>Abril et al 2005</td>
<td></td>
</tr>
<tr>
<td>Petit Saut</td>
<td>300</td>
<td>6</td>
<td>11</td>
<td>4</td>
<td>15</td>
<td>Abril et al 2005</td>
<td></td>
</tr>
<tr>
<td>Petit Saut</td>
<td>300</td>
<td>7</td>
<td>1808</td>
<td>26</td>
<td>4</td>
<td>Abril et al 2005</td>
<td></td>
</tr>
<tr>
<td>Petit Saut</td>
<td>300</td>
<td>8</td>
<td>1473</td>
<td>20</td>
<td>2</td>
<td>Abril et al 2005</td>
<td></td>
</tr>
<tr>
<td>Petit Saut</td>
<td>300</td>
<td>9</td>
<td>2009</td>
<td>18</td>
<td>1</td>
<td>Abril et al 2005</td>
<td></td>
</tr>
<tr>
<td>Petit Saut</td>
<td>300</td>
<td>10</td>
<td>2511</td>
<td>17</td>
<td>1</td>
<td>Abril et al 2005</td>
<td></td>
</tr>
<tr>
<td>Petit Saut</td>
<td>270-365</td>
<td>(wet)</td>
<td>5852 (5104)</td>
<td>-</td>
<td>-</td>
<td>123.2 (140.8)</td>
<td>Guerin et al, 2006</td>
</tr>
<tr>
<td>Petit Saut</td>
<td>270-365</td>
<td>(dry)</td>
<td>5764 (4840)</td>
<td>-</td>
<td>-</td>
<td>43.2 (25.6)</td>
<td>Guerin et al, 2006</td>
</tr>
<tr>
<td>Petit Saut</td>
<td>270-365</td>
<td>(dry)</td>
<td>4532 (2992)</td>
<td>-</td>
<td>-</td>
<td>1.6 (1.6)</td>
<td>Guerin et al, 2006</td>
</tr>
<tr>
<td>Petit Saut</td>
<td>270-365</td>
<td>(wet)</td>
<td>4488 (6292)</td>
<td>-</td>
<td>-</td>
<td>11.2 (8)</td>
<td>Guerin et al, 2006</td>
</tr>
<tr>
<td>Balbina</td>
<td>1770</td>
<td>17-19</td>
<td>13845 (1260-31270)</td>
<td>63* (7-460)</td>
<td>-</td>
<td>63</td>
<td>Kemenes et al, 2007, 2011</td>
</tr>
<tr>
<td>Balbina</td>
<td>1560-2360</td>
<td>17</td>
<td>3344 (2024)</td>
<td>-</td>
<td>-</td>
<td>33.6* (48)</td>
<td>Guerin et al, 2006</td>
</tr>
<tr>
<td>Tucuruí</td>
<td>2430</td>
<td>14</td>
<td>10453 (1314-142723)</td>
<td>192.2 (0.03-2889)</td>
<td>13.2 (0.01-106)</td>
<td>205.4</td>
<td>Santos et al, 2006</td>
</tr>
<tr>
<td>Tucuruí</td>
<td>2430</td>
<td>15</td>
<td>6516 (457-32291)</td>
<td>10.9 (4.44-28.53)</td>
<td>2.5 (0.92-21.2)</td>
<td>13.4</td>
<td>Santos et al, 2006</td>
</tr>
<tr>
<td>Tucuruí</td>
<td>2800</td>
<td>16-17</td>
<td>13.82* (22.94)</td>
<td>-</td>
<td>-</td>
<td>13.82* (22.94)</td>
<td>Lima et al, 2005</td>
</tr>
<tr>
<td>Samuel</td>
<td>559</td>
<td>9</td>
<td>8087 (2313-16345)</td>
<td>164.3 (4.9-2375)</td>
<td>19.3 (0.0001-67)</td>
<td>183.6</td>
<td>Santos et al, 2006</td>
</tr>
<tr>
<td>Samuel</td>
<td>559</td>
<td>10</td>
<td>6808 (2200-24283)</td>
<td>10.8 (6.13-17.6)</td>
<td>13.6 (0.07-37.6)</td>
<td>24.4</td>
<td>Santos et al, 2006</td>
</tr>
<tr>
<td>Samuel</td>
<td>559</td>
<td>11-12</td>
<td>71.19* (107.4)</td>
<td>-</td>
<td>71.19* (107.4)</td>
<td>Liñán et al, 2005</td>
<td></td>
</tr>
<tr>
<td>Samuel</td>
<td>180-559</td>
<td>16</td>
<td>42944 (53372)</td>
<td>-</td>
<td>-</td>
<td>80 (94.4)</td>
<td>Guerin et al, 2006</td>
</tr>
</tbody>
</table>

Statistics

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Min</th>
<th>Max</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>1473</td>
<td>205</td>
<td>8028</td>
<td>9891</td>
<td>15</td>
</tr>
<tr>
<td>Max</td>
<td>42944</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Diffusion and ebullition
** The model does not account for CO₂ ebullitive fluxes from the reservoir as these fluxes are negligible for the overall balance (Abril et al. 2005; Santos et al. 2006).

a - Flux rates calculated from the total annual emissions from Table 4 from Abril et al (2005), using average reservoir surface area of 300 km²
b - Flux rates reported in Table 3 from Guerin et al (2006)
Figure S10 - A: Histogram and fitted distribution for res\text{CH}_4. Exponential distribution (scale parameter (\mu) = 51.6) for the CH\textsubscript{4} diffusion plus ebullition dataset. B: Histogram and fitted distribution for res\text{CO}_2. Rayleigh fitted distribution (scale parameter (b) = 4589.8) for the CO\textsubscript{2} diffusion rates dataset excluding Samuel (16 years).

6.3.2 Outlet degassing (d\text{eg}_{\text{CO}_2} and d\text{eg}_{\text{Ch}_4})

Outlet degassing results from pressure and temperature changes that occur on discharge flows from low-level outlets, such as turbines and spillways. Outlet degassing emissions are estimated by the multiplication of the difference in gas concentration between upstream (reservoir) and downstream the dam (just after outlet structures), and the water volume that passes through the hydraulic structures (Kemenes, Forsberg & Melack 2007; 2011; Abril et al. 2005).

Degassing emissions were reported for the Petit Saut (Abril et al. 2005), Balbina (Kemenes, Forsberg & Melack 2007; 2011), and Tucuruí (Fearnside 2002) reservoirs (See Table S15). Most of the available data come from the Petit Saut reservoir, where degassing emission
stabilization occurred after three years of the impoundment for CH₄ and 5 years for CO₂ (Abril et al. 2005). Unfortunately, there are not sufficient data (6 and 9 data points, for CO₂ and CH₄, respectively) to develop robust probability functions for these degassing rates. Thus, we assumed uniform distributions defined by the maximum and minimum values from our degassing data points to describe the uncertain of $\text{deg}_\text{CO}_2$ and $\text{deg}_\text{CH}_4$. $\text{deg}_\text{CO}_2$ varied from 50 to 90 mg of CO₂ m⁻² day⁻¹ and $\text{deg}_\text{CH}_4$ range from 50 to 900 mg of CH₄ m⁻² day⁻¹.

**Table S15 - Outlet Degassing Emissions in tropical reservoirs**

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Age when sampled</th>
<th>Mean Flow (m³/s)</th>
<th>Reservoir Area (km²)</th>
<th>CO₂ Degassing per reservoir area (mg CO₂ m⁻² day⁻¹)</th>
<th>CH₄ Degassing per reservoir area (mg CH₄ m⁻² day⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petit Saut*</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>15280</td>
<td>186</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>15230</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>10100</td>
<td>92</td>
<td>11320</td>
<td>138</td>
<td>Abril et al, 2005</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>267***</td>
<td>300</td>
<td>7700</td>
<td>70</td>
<td>18460</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>5300</td>
<td>48</td>
<td>9380</td>
<td>114</td>
<td>Abril et al, 2005</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>7300</td>
<td>67</td>
<td>12570</td>
<td>153</td>
<td>Abril et al, 2005</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>9300</td>
<td>85</td>
<td>5189</td>
<td>63</td>
<td>Abril et al, 2005</td>
</tr>
<tr>
<td>Tucuruí**</td>
<td>5</td>
<td>3558</td>
<td>2875</td>
<td>-</td>
<td>702000</td>
<td>892</td>
</tr>
</tbody>
</table>

**Statistics**

- **Min.** 48
- **Max.** 92
- **Average** 68
- **Standard Deviation** 17
- **n** 6

In the case of low RT reservoirs in the Amazon, the only available data for degassing fluxes comes from the Santo Antônio reservoir. Degassing/downstream CH₄ emissions from the
Santo Antônio dam in the first year were estimated to be 5.6 Gg (Fearnside 2015b). Thus, we applied the Santo Antônio flux (75 mg of CH$_4$ m$^{-2}$ day$^{-1}$) to define deg/down$_{CH_4}$ in TD-low RT model. As previously mentioned, due to the high uncertainty of this value (Fearnside 2015b), we present the results with and without this flux.

Note that degassing emissions are reported in total annual mass of CO$_2$ and CH$_4$. To standardize the degassing emissions, we divided the total annual emissions by the reservoir area (Table S15). In Table S16, we standardized the degassing emission from Amazonian reservoirs using two different criteria: degassing per water volume and degassing per reservoir area.

**Table S16 – Standardization methods for degassing**

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Reservoir Age</th>
<th>Area (km$^2$)</th>
<th>Degassing (Mg C yr$^{-1}$)</th>
<th>Mean Flow (m$^3$/s)</th>
<th>CH$_4$ Degassing (mg CH$_4$ per m$^3$ of water)</th>
<th>CH$_4$ Degassing (mg CH$_4$ m$^{-2}$ day$^{-1}$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petit Saut</td>
<td>3</td>
<td>15280</td>
<td>267</td>
<td>2.42</td>
<td>186</td>
<td>Abril et al, 2005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>15230</td>
<td>267</td>
<td>2.41</td>
<td>185</td>
<td>Abril et al, 2005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>11320</td>
<td>267</td>
<td>1.79</td>
<td>138</td>
<td>Abril et al, 2005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>300</td>
<td>18460</td>
<td>2.92</td>
<td>225</td>
<td>Abril et al, 2005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>9380</td>
<td>267</td>
<td>1.49</td>
<td>114</td>
<td>Abril et al, 2005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>12570</td>
<td>267</td>
<td>1.99</td>
<td>153</td>
<td>Abril et al, 2005</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>5189</td>
<td>267</td>
<td>0.82</td>
<td>63</td>
<td>Abril et al, 2005</td>
<td></td>
</tr>
<tr>
<td>Tucuruí</td>
<td>5</td>
<td>2875</td>
<td>702000</td>
<td>8.34</td>
<td>892</td>
<td>Fearnside, 2002</td>
<td></td>
</tr>
<tr>
<td>Santo Antônio*</td>
<td>1</td>
<td>273</td>
<td>5569</td>
<td>18806</td>
<td>0.01</td>
<td>75</td>
<td>Fearnside, 2015</td>
</tr>
</tbody>
</table>

*CH$_4$ degassing/downstream emission corresponds to 35% of total emissions (15,911 Mg C/year)

We applied the area instead of the flow as the standardization for the degassing fluxes because this method is more physically appropriate. Degassing emissions are linearly correlated to CO$_2$ and CH$_4$ concentration in the reservoir water (Abril et al. 2005). Moreover, the gas concentrations in the reservoir are highly correlated to the RT, which is a function of reservoir flow and volume. However, the most important issue here is not the volume of water, but the
quantity of the CH$_4$ produced. CH$_4$ production is correlated with the C stock, which is a function of the reservoir area. Finally, the standardization by area was also applied in previous literature (Goldenfum 2010).

In terms of degassing per water volume, the results for the Santo Antônio reservoir are two orders of magnitude lower compared to the other high-RT reservoirs. This result is predictable given that degassing/downstream emissions are positively correlated to CH$_4$ concentration in the reservoir (Abril et al. 2005), and CH$_4$ concentration is expected to be lower in low RT reservoirs when compared to those concentrations in high RT reservoirs (DelSontro et al. 2010).

With respect to the standardization by area, the Santo Antônio reservoir flux has one of the lowest values, but in the same order of magnitude compared to the other dams. Given that the estimate is based on data collect in the first operational year and reservoir emissions decrease after the first few years (Abril et al. 2005; Demarty & Bastien 2011), the standardization by area also suggests that the degassing emissions in low-RT reservoirs are lower compared to high RT reservoirs.

6.3.3 Downstream Emissions (down$_{CO2}$ and down$_{CH4}$)

The water that passes through the dam structures and runs through the rivers still contains dissolved and particulate organic C, as well as dissolved CO$_2$ and CH$_4$ that were not released by degassing immediately after the dam and are thus transferred downstream (Guérin et al. 2006; Kemenes, Forsberg & Melack 2007; 2011).

Table S17 presents downstream emission fluxes (down$_{CO2}$ and down$_{CH4}$). Direct measurements of downstream fluxes from dams in tropical forests are available within a distance
of around 30 to 40 km after the dam at Balbina (Guérin et al. 2006; Kemenes, Forsberg & Melack 2007; 2011), Samuel, and Petit Saut (Guérin et al. 2006). The authors found that rivers downstream of dams contained high concentrations of CH$_4$ and CO$_2$ originating from reservoir hypolimnions (the bottom layer of an stratified reservoir). Diffusive fluxes in the river gradually release this CH$_4$ and CO$_2$. Downstream CH$_4$ and CO$_2$ fluxes were on average 165 and 7 times higher than diffusive and ebbulitive fluxes measured in the reservoir, respectively (Guérin et al. 2006). Downstream concentrations presented a decreasing trend as a function of distance, but the slope of the relation varied across the dams. CH$_4$ concentrations decreased faster than CO$_2$ (Guérin et al. 2006). We defined the model downstream boundary as 40 km downstream the dam because the available data is constrained to this range.

Table S17 - Average downstream emissions in forested tropical reservoirs. Values in the brackets represent the reported standard deviation or range.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Reservoir Area (km$^2$)</th>
<th>Age when Sampled (season)</th>
<th>River Downstream Emissions (mg CO$_2$/m$^2$.day)</th>
<th>River Downstream Emissions (mg CH$_4$/m$^2$.day)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petit Saut</td>
<td>270-365</td>
<td>9 (wet)</td>
<td>41580 (14960)</td>
<td>720 (544)</td>
<td>Guerin, 2006</td>
</tr>
<tr>
<td>Petit Saut</td>
<td>270-365</td>
<td>9 (dry)</td>
<td>36476 (9152)</td>
<td>944 (944)</td>
<td>Guerin, 2006</td>
</tr>
<tr>
<td>Petit Saut</td>
<td>270-365</td>
<td>11 (dry)</td>
<td>35288 (16016)</td>
<td>1344 (608)</td>
<td>Guerin, 2006</td>
</tr>
<tr>
<td>Petit Saut</td>
<td>270-365</td>
<td>11 (wet)</td>
<td>29480 (4180)</td>
<td>752 (432)</td>
<td>Guerin, 2006</td>
</tr>
<tr>
<td>Balbina</td>
<td>1560 - 2360</td>
<td>17</td>
<td>18128 (4180)</td>
<td>1824 (1056)</td>
<td>Guerin, 2006</td>
</tr>
<tr>
<td>Samuel</td>
<td>180-559</td>
<td>16</td>
<td>65736 (42372)</td>
<td>192 (208)</td>
<td>Guerin, 2006</td>
</tr>
</tbody>
</table>

Statistics

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17563</td>
<td>65736</td>
<td>34893</td>
<td>16378</td>
</tr>
<tr>
<td>n</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

164
The limitation of data points for outlet degassing and downstream emissions led to the adoption of a uniform distribution to represent the uncertainty and variability in these flux rates. The uniform distributions were limited by the maximum and minimum data values for each emission rate distribution. We applied these fluxes only for the high RT reservoirs.

6.3.4 Fitted distributions summary

Table S18 summarizes the probability distributions assigned to each input of the Monte Carlo Simulation.

<table>
<thead>
<tr>
<th>Flux</th>
<th>Distribution</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>res CO2</td>
<td>Rayleigh</td>
<td>scale parameter (b) = 4589.8</td>
</tr>
<tr>
<td>res CH4</td>
<td>Exponential</td>
<td>(scale parameter (m)= 51.6)</td>
</tr>
<tr>
<td>deg CO2</td>
<td>Uniform</td>
<td>(max=90, min=50)</td>
</tr>
<tr>
<td>deg CH4</td>
<td>Uniform</td>
<td>(max=900, min=50)</td>
</tr>
<tr>
<td>down CO2</td>
<td>Uniform</td>
<td>(max=65,700, min=17,600)</td>
</tr>
<tr>
<td>down CH4</td>
<td>Uniform</td>
<td>(max=1,800, min= 190)</td>
</tr>
<tr>
<td>nat CO2 - Black Water</td>
<td>Rayleigh</td>
<td>(scale (b)= 1.78e+04)</td>
</tr>
<tr>
<td>nat CO2 - Clear Water</td>
<td>Generalized Extreme Value</td>
<td>(shape (k) = 0.296; Location (µ)=2.82e+03; scale (σ) = 3.34e+03)</td>
</tr>
<tr>
<td>nat CO2 - White Water</td>
<td>Rayleigh</td>
<td>(scale (b)= 1.6336e+04)</td>
</tr>
<tr>
<td>nat CH4 - Black Water</td>
<td>Inverse Gaussian</td>
<td>(mean (m)= 7.18, shape (l)=3.88);</td>
</tr>
<tr>
<td>nat CH4 - Clear Water</td>
<td>Inverse Gaussian</td>
<td>(mean (m)= 72.95, shape (l)=10.81)</td>
</tr>
<tr>
<td>nat CH4 - White Water</td>
<td>Generalized Pareto</td>
<td>(shape (k) = 0.6947; scale (s) = 4.4007; thresholds (q)=0.0899)</td>
</tr>
</tbody>
</table>
6.4 Complementary Results and Discussion

Table S19 reports the average and 95% confidence interval from the Monte Carlo simulation outcomes in a hundred years (NRE). These results correspond to the same values presented in Figure 2-1 in Chapter 2.

Table S19 - Simulation results: average and 95% Confidence Interval (2.5% - 97.5%). Net reservoir emissions in a hundred years.

<table>
<thead>
<tr>
<th>Bottom-up</th>
<th>Top-Down</th>
</tr>
</thead>
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* indicate storage dams

Table S20 and S21 present the annual average and 95% confidence interval from the Monte Carlo simulation outcomes according to the reservoir age for both TD and BU approaches. The decreasing emissions through the time are explained by the modeling assumptions described in this document. In the case of the TD approaches, the steady state
assumption (6° to 100° year) and the multiplier factors assumed model the first pulse of emissions (1° to 5°) explain the emissions temporal variability. On the other hand, the decreasing degradation function (module 1 and 2) justifies the reduction of emission over time in the BU model. These tables underline the higher impact from hydropower plants in the first years of operation.
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Figure S11 presents the total net reservoir emission over a period for a hundred years in CO$_2$eq. The results illustrate the higher contribution of CH$_4$ to the potential climate impacts from these reservoirs compared to the total emissions in terms of C mass (Figure 2-1 in Chapter 2).
Figure S11 - Net reservoirs emissions in CO$_2$eq (methane GWP equals 34). Mean net GHG emission over 100 years (circle) and 95% confidence intervals (error bars). Black numbers represent the mean GHG net emissions and confidence intervals in parenthesis. (*) Indicates high RT reservoirs.
**TD Approach Low RT Reservoirs**

Figure S12 breaks down the contribution of each emission pathway to the net emissions (mean) for the top-down approach in low RT reservoirs and presents the results in total mass of C and in CO₂eq using methane GWP equal 86 (20-year) and 34 (100-year). It shows the gross fluxes from the reservoir system (Figures S12A, S12C and S12E) and the natural river system (Figures S12B, S12D and S12F).

In terms of C mass (Figures S12A and S12B), CO₂ emissions from the main channel and bays/tributaries are the largest contributors to C fluxes (reservoir system). On the other hand, when including the GWP as a metric for climate impacts, Figure S12C and S12F show that CH₄ fluxes account for the majority of the total emissions in CO₂ equivalents. In the average scenario, natural emissions before the impoundment account for 15% to 45% of the reservoir system emissions (comparing Figure S12A and S12B).
Figure S12: TD model mean results for the low residence time reservoirs in a hundred years by emission pathway. A- Reservoir system in C. B- River System (Natural Emissions) in C. C - Reservoir system in CO₂eq using the 20-year global warming potential (GWP) value for CH₄. D - River System in CO₂eq using the 20-year GWP value for CH₄. E - Reservoir system in CO₂eq using the 100-year GWP value for CH₄. F - River System in CO₂eq using the 100-year GWP value for CH₄.
6.4.1 Emission factors

Table S22 and S23 present the emission factor simulation results according to the reservoir age. Both approaches show the higher impact of hydropower in the first years of operation. Again, the model features and assumptions previously described in this document explain the decreasing emission factors according to the reservoir aging.
Table S22 – Annual emissions factors (kg CO₂eq MWh⁻¹) according to the reservoir age: average and 95% Confidence Interval (2.5% - 97.5%). Methane GPW equals 34.

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</table>

For these calculations, we assumed that the emissions from the cleared vegetation (BU – Module 3) are uniformly released within a period of 30 years.
Table S23 – Annual emissions factor (kg CO₂eq MWh⁻¹) according to the reservoir age: average and 95% Confidence Interval (2.5% - 97.5%). Methane GPW equals 86.

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For these calculations, we assumed that the emissions from the cleared vegetation (BU – Module 3) are uniformly released within a period of 30 years.
6.4.2 The importance of vegetation clearing

To investigate the importance of vegetation clearing in the GHG emissions from Amazon reservoirs, we compared the emissions results from each BU approach module. Table S24 presents the simulation mean and 95% confidence interval in total mass of C for each module: only flooded soils, only flooded foliage, and cleared vegetation.

Table S24 – Total reservoir emissions over a 100-years in terms of carbon mass: average and 95% Confidence Interval (2.5% - 97.5%) according to the carbon stock.

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<td>0.1 (0-0.1) 0.3 (0-0)</td>
<td>0.02 (0-0.04) 0.07 (0.1-0.1)</td>
<td>0.36 (0.3-0.4) 0.8 (0.6-1)</td>
<td></td>
</tr>
<tr>
<td>Cachoeira dos Patos</td>
<td>0.2 (0-0.4) 0.9 (1-1)</td>
<td>0.06 (0-0.1) 0.24 (0.2-0.2)</td>
<td>1 (0.9-1.2) 2 (1.9-3)</td>
<td></td>
</tr>
<tr>
<td>Colíder</td>
<td>0.2 (0-1) 1.2 (1-2)</td>
<td>0.1 (0-0.2) 0.35 (0.3-0.4)</td>
<td>0.8 (0.7-0.9) 3 (2-3)</td>
<td></td>
</tr>
<tr>
<td>Ferreira Gomes</td>
<td>0.02 (0-0.04) 0.1 (0.06-0.14)</td>
<td>0.01 (0-0.01) 0.03 (0-0)</td>
<td>0.06 (0.05-0.1) 0.2 (0.0-0.3)</td>
<td></td>
</tr>
<tr>
<td>Jamanxim</td>
<td>0.1 (0-0.3) 0.6 (0-1)</td>
<td>0.04 (0-0.1) 0.16 (0.2-0.2)</td>
<td>0.9 (0.8-0.96) 1.8 (1-2)</td>
<td></td>
</tr>
<tr>
<td>Jatobá</td>
<td>0.5 (0-1) 2.4 (1-3)</td>
<td>0.2 (0-0.3) 0.64 (0.6-0.8)</td>
<td>2.4 (2.1-2.6) 6 (5-7)</td>
<td></td>
</tr>
<tr>
<td>Jirau</td>
<td>0.4 (0-1) 2 (1-3)</td>
<td>0.1 (0-0.3) 0.54 (0.5-0.6)</td>
<td>2.5 (2.3-2.8) 6 (4-7)</td>
<td></td>
</tr>
<tr>
<td>Marabá</td>
<td>1.2 (0-3) 5.8 (4-8)</td>
<td>0.4 (0.1-0.9) 1.62 (1.4-1.8)</td>
<td>4.5 (4-5) 13 (10-17)</td>
<td></td>
</tr>
<tr>
<td>Salto Augusto de Baixo</td>
<td>0.1 (0-0.3) 0.7 (0-1)</td>
<td>0.04 (0-0.1) 0.19 (0.2-0.2)</td>
<td>0.9 (0.8-1) 2 (2-2)</td>
<td></td>
</tr>
<tr>
<td>Santo Antônio</td>
<td>0.3 (0-1) 1.5 (1-2)</td>
<td>0.1 (0-0.2) 0.41 (0.4-0.4)</td>
<td>1.6 (1-2) 4 (3-5)</td>
<td></td>
</tr>
<tr>
<td>São Luís do Tapajós</td>
<td>0.7 (0-1) 3.3 (2-5)</td>
<td>0.2 (0-0.5) 0.93 (0.9-1)</td>
<td>4.5 (4-5) 10 (8-12)</td>
<td></td>
</tr>
<tr>
<td>São Manoel</td>
<td>0.1 (0-0.2) 0.5 (0-1)</td>
<td>0.03 (0-0.1) 0.13 (0.1-0.1)</td>
<td>0.63 (0.6-0.7) 1 (1-2)</td>
<td></td>
</tr>
<tr>
<td>São Simão Alto</td>
<td>0.4 (0-1) 2 (1-3)</td>
<td>0.1 (0-0.3) 0.55 (0.5-0.6)</td>
<td>3 (2.7-3.3) 6 (5-7)</td>
<td></td>
</tr>
<tr>
<td>Sinop</td>
<td>0.5 (0-1) 2.6 (2-4)</td>
<td>0.2 (0-0.4) 0.73 (0.6-0.8)</td>
<td>1.7 (1-2) 6 (4-7)</td>
<td></td>
</tr>
<tr>
<td>Teles Pires</td>
<td>0.2 (0-0) 1 (1-1)</td>
<td>0.1 (0-0.2) 0.29 (0.3-0.3)</td>
<td>0.9 (0.8-1) 3 (2-3)</td>
<td></td>
</tr>
</tbody>
</table>
Compared to the emissions from soils only, Table S24 results show that the flooded foliage contributes to an average increase of 33% and 28% of the CH₄ and CO₂ emissions, respectively. These results underline the importance of the vegetation clearing requirement and the effect of an inefficient biomass removal. CO₂ emissions from the cleared vegetation are in the same order of magnitude compared to the CO₂ emissions from soils alone, representing a significant component of the budget.

Table S25 shows the effect of flooded foliage and vegetation clearing on the emissions factors of each reservoir. Compared to the C in the soils only, Table S25 results indicate the emission factors increase on average 64% when taking into account the emissions from flooded foliage and cleared biomass.
Table S25 – Total reservoir emissions over a 100-years in terms CO₂eq: average and 95% Confidence Interval (2.5% - 97.5%) according to the carbon stock. GWP equal 34 (100 years)

<table>
<thead>
<tr>
<th>Projects</th>
<th>Flooded soils only</th>
<th></th>
<th>Flooded soils and foliage, plus cleared biomass</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Average Emission Factor</td>
<td>Total</td>
<td>Average Emission Factor</td>
</tr>
<tr>
<td></td>
<td>Tg CO₂eq</td>
<td>kg CO₂eq MWh⁻¹</td>
<td>Tg CO₂eq</td>
<td>kg CO₂eq MWh⁻¹</td>
</tr>
<tr>
<td>Belo Monte</td>
<td>29 (11-55)</td>
<td>7 (3-14)</td>
<td>47 (24-82)</td>
<td>12 (6-21)</td>
</tr>
<tr>
<td>Bem Querer</td>
<td>47 (18-89)</td>
<td>138 (54-261)</td>
<td>74 (36-129)</td>
<td>216 (104-377)</td>
</tr>
<tr>
<td>Cachoeira do Caí</td>
<td>40 (16-76)</td>
<td>112 (44-211)</td>
<td>74 (41-121)</td>
<td>205 (115-336)</td>
</tr>
<tr>
<td>Cachoeira do Caldeirão</td>
<td>3 (1-6)</td>
<td>32 (12-60)</td>
<td>6 (3-10)</td>
<td>54 (29-93)</td>
</tr>
<tr>
<td>Cachoeira dos Patos</td>
<td>11 (4-21)</td>
<td>74 (29-140)</td>
<td>18 (9-31)</td>
<td>123 (64-209)</td>
</tr>
<tr>
<td>Colíder</td>
<td>15 (6-30)</td>
<td>105 (41-200)</td>
<td>23 (11-42)</td>
<td>158 (74-283)</td>
</tr>
<tr>
<td>Ferreira Gomes</td>
<td>1 (0-2)</td>
<td>9 (4-18)</td>
<td>2 (1-3)</td>
<td>14 (7-25)</td>
</tr>
<tr>
<td>Jamanxim</td>
<td>7 (3-14)</td>
<td>18 (7-34)</td>
<td>13 (7-22)</td>
<td>31 (17-52)</td>
</tr>
<tr>
<td>Jatobá</td>
<td>29 (12-57)</td>
<td>26 (10-50)</td>
<td>47 (24-82)</td>
<td>42 (21-73)</td>
</tr>
<tr>
<td>Jirau</td>
<td>25 (10-47)</td>
<td>13 (5-24)</td>
<td>42 (22-70)</td>
<td>22 (11-37)</td>
</tr>
<tr>
<td>Marabá</td>
<td>74 (28-139)</td>
<td>72 (27-135)</td>
<td>113 (54-201)</td>
<td>110 (53-196)</td>
</tr>
<tr>
<td>Salto Augusto de Baixo</td>
<td>9 (3-16)</td>
<td>12 (5-23)</td>
<td>14 (8-25)</td>
<td>21 (11-36)</td>
</tr>
<tr>
<td>Santo Antônio</td>
<td>19 (7-35)</td>
<td>10 (4-20)</td>
<td>31 (16-52)</td>
<td>17 (9-29)</td>
</tr>
<tr>
<td>São Luís do Tapajós</td>
<td>42 (16-81)</td>
<td>15 (6-29)</td>
<td>72 (38-123)</td>
<td>26 (14-45)</td>
</tr>
<tr>
<td>São Manoel</td>
<td>6 (2-11)</td>
<td>18 (7-34)</td>
<td>10 (5-17)</td>
<td>31 (16-53)</td>
</tr>
<tr>
<td>São Simão Alto</td>
<td>25 (10-47)</td>
<td>15 (6-28)</td>
<td>44 (24-73)</td>
<td>26 (14-44)</td>
</tr>
<tr>
<td>Sinop</td>
<td>33 (13-62)</td>
<td>187 (73-354)</td>
<td>49 (23-88)</td>
<td>281 (132-501)</td>
</tr>
<tr>
<td>Teles Pires</td>
<td>13 (5-25)</td>
<td>15 (6-29)</td>
<td>21 (10-37)</td>
<td>24 (12-43)</td>
</tr>
</tbody>
</table>

With respect to vegetation clearing, the following mitigation measures are recommended:

1. Instead of burning or burying the cleared vegetation, the wood resources should only be employed in low decay end uses such as construction material and furniture.

2. The reforestation of a previously deforested area with at least the same size of the reservoir area to replace the C stock lost by the vegetation clearing.

3. Improve the enforcement of the vegetation clearing and authorize the reservoir filling just after a complete biomass removal including leaves and small foliage.
4. Vegetation clearing should take place just before the reservoir filling starts in order to reduce the period for biomass regrowth in the reservoir area.

6.4.3 Sensitivity Analysis: reservoir area from projects with storage capacity

The reservoir surface area ($A_{\text{RES}}$) is a source of uncertainty for storage reservoirs because of the seasonal water level variation related to variability of river flows and reservoir operation. $A_{\text{RES}}$ variations can affect our estimates, particularly the TD approach, where $A_{\text{RES}}$ is an important input to scale the GHG fluxes.

In the case of the BU approach, the periodical variation of the reservoir level may affect the proliferation of biomass in the drawdown zone, annually increasing the flooded C stock available for CH$_4$ production. The variation of the reservoir area, however, does not affect the initial C stock assessed by the BU model as the C stock available continues to be defined by the maximum water level. At this point, we cannot estimate the seasonal increment of the biomass in the drawdown zones because of lack of studies regarding the specific contribution related to these areas. The TD model estimates, however, indirectly account for these inputs because the probability distributions for the TD model are based on measurements in the air/water interface, which captures emissions from all input sources, including the upstream and lateral inputs, such as the biomass from drawdown zones.

To evaluate the effect of the variation of the $A_{\text{RES}}$ in the TD model, we performed a sensitivity analysis using an alternative reference value to define the $A_{\text{RES}}$. Table S26 present the sensitivity analysis results using two reservoir areas: at the normal maximum (baseline), and at normal average water level (see Table S10 for details). As expected, Table S26 shows that the use of a lower reservoir area leads to lower emissions. However, the variation of the surface area
does not change the conclusion about the high level of emissions from these reservoirs, which are comparable to those of thermal power plants.

Table S26 - Sensitivity Analysis results for storage reservoirs. Simulation results over a period of 100 years: average and 95% Confidence Interval (2.5% - 97.5%). GWP equals 34.

<table>
<thead>
<tr>
<th>Projects</th>
<th>Normal Maximum Water Level</th>
<th>Normal Average Water Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$CO_2$ Tg C</td>
<td>$CH_4$ Tg C</td>
</tr>
<tr>
<td>Cachoeira do Caí</td>
<td>22</td>
<td>7</td>
</tr>
<tr>
<td>Cachoeira dos Patos</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Sinop</td>
<td>24</td>
<td>5</td>
</tr>
</tbody>
</table>

6.4.4 Sensitivity Analysis: degassing/downstream fluxes in low RT reservoirs

Because only one estimate from Santo Antônio reservoirs (Fearnside 2015b) is available for modeling the degassing/downstream fluxes in low RT reservoirs (TD approach), we present the results for low RT reservoir with and without the degassing/downstream estimate. Table S27 presents the results in terms of mass of C and Table S28 presents the effect of degassing in CO$_2$eq. The results show that degassing/downstream emissions can be an important part of the budget for low RT reservoirs. Nevertheless, more data are necessary to confirm the contribution of these pathways in low RT reservoirs.
Table S27 - Degassing/downstream sensitivity analysis of total emission fluxes for low RT reservoirs. Simulation results over a period of 100 years: average and 95% Confidence Interval (2.5% - 97.5%).

<table>
<thead>
<tr>
<th>Projects</th>
<th>Reservoir Surface Emissions</th>
<th>Degassing/downstream</th>
<th>Total with degassing/downstream</th>
<th>Total without degassing/downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$CO_2$</td>
<td>$CH_4$</td>
<td>$CH_4$</td>
<td>$Total$</td>
</tr>
<tr>
<td></td>
<td>Tg C</td>
<td>Tg C</td>
<td>Tg C</td>
<td>Tg C</td>
</tr>
<tr>
<td>Belo Monte</td>
<td>18 (0-66)</td>
<td>0.6 (0-4.3)</td>
<td>1.25</td>
<td>20 (1-67)</td>
</tr>
<tr>
<td>Bem Querer</td>
<td>29 (2-99)</td>
<td>0.9 (0.1-5.3)</td>
<td>1.36</td>
<td>31 (4-100)</td>
</tr>
<tr>
<td>Cachoeira do Caldeirão</td>
<td>2 (0-6.4)</td>
<td>0 (0-0.1)</td>
<td>0.12</td>
<td>2.2 (0-6.5)</td>
</tr>
<tr>
<td>Colider</td>
<td>9.5 (1-29)</td>
<td>0.3 (0-1.5)</td>
<td>0.42</td>
<td>10 (2-30)</td>
</tr>
<tr>
<td>Ferreira Gomes</td>
<td>0.75 (0-2.5)</td>
<td>0.01 (0-0.02)</td>
<td>0.04</td>
<td>0.8 (0-2.5)</td>
</tr>
<tr>
<td>Jatobá</td>
<td>18 (4-42)</td>
<td>0.5 (0-2)</td>
<td>1.57</td>
<td>20 (6-44)</td>
</tr>
<tr>
<td>Jirau</td>
<td>36 (11-71)</td>
<td>0.1 (0-0.5)</td>
<td>0.74</td>
<td>37 (12-72)</td>
</tr>
<tr>
<td>Marabá</td>
<td>45 (2-160)</td>
<td>1.4 (0.1-9.4)</td>
<td>2.49</td>
<td>49 (5-160)</td>
</tr>
<tr>
<td>Salto Augusto de Baixo</td>
<td>5.1 (1-14)</td>
<td>0.2 (0-0.8)</td>
<td>0.30</td>
<td>5.6 (1-15)</td>
</tr>
<tr>
<td>Santo Antônio</td>
<td>28 (8-56)</td>
<td>0.1 (0-0.5)</td>
<td>0.66</td>
<td>29 (9-57)</td>
</tr>
<tr>
<td>São Luís do Tapajos</td>
<td>25 (6-66)</td>
<td>0.7 (0.1-3.3)</td>
<td>1.76</td>
<td>28 (8-68)</td>
</tr>
<tr>
<td>São Manoel</td>
<td>3.5 (0-11)</td>
<td>0.1 (0-0.6)</td>
<td>0.16</td>
<td>3.7 (1-12)</td>
</tr>
<tr>
<td>São Simão Alto</td>
<td>15 (3-40)</td>
<td>0.4 (0-2.1)</td>
<td>0.69</td>
<td>16 (4-41)</td>
</tr>
<tr>
<td>Teles Pires</td>
<td>7.9 (1-22)</td>
<td>0.2 (0-1.3)</td>
<td>0.37</td>
<td>8.5 (2-23)</td>
</tr>
</tbody>
</table>

Table S28 - Degassing/downstream sensitivity analysis of the emission factor for low RT reservoirs. Simulation results over a period of 100 years: average and 95% Confidence Interval (2.5% - 97.5%). Methane GWP equals 34.

<table>
<thead>
<tr>
<th>Projects</th>
<th>Emission Factor with degassing/downstream</th>
<th>Emission factor without degassing/downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg CO$_2$eq MWh$^{-1}$</td>
<td>kg CO$_2$eq MWh$^{-1}$</td>
</tr>
<tr>
<td>Belo Monte</td>
<td>35 (15-92)</td>
<td>21 (2-79)</td>
</tr>
<tr>
<td>Bem Querer</td>
<td>570 (227-1500)</td>
<td>400 (60-1400)</td>
</tr>
<tr>
<td>Cachoeira do Caldeirão</td>
<td>120 (61-260)</td>
<td>73 (15-210)</td>
</tr>
<tr>
<td>Colider</td>
<td>420 (186-1000)</td>
<td>300 (67-880)</td>
</tr>
<tr>
<td>Ferreira Gomes</td>
<td>35 (17-80)</td>
<td>21 (3-66)</td>
</tr>
<tr>
<td>Jatobá</td>
<td>130 (80-230)</td>
<td>71 (21-170)</td>
</tr>
<tr>
<td>Jirau</td>
<td>83 (37-150)</td>
<td>67 (21-130)</td>
</tr>
<tr>
<td>Marabá</td>
<td>310 (127-820)</td>
<td>200 (25-710)</td>
</tr>
<tr>
<td>Salto Augusto de Baixo</td>
<td>53 (28-110)</td>
<td>35 (9-95)</td>
</tr>
<tr>
<td>Santo Antônio</td>
<td>72 (33-130)</td>
<td>56 (17-110)</td>
</tr>
<tr>
<td>São Luís do Tapajos</td>
<td>69 (39-130)</td>
<td>42 (12-110)</td>
</tr>
<tr>
<td>São Manoel</td>
<td>72 (31-190)</td>
<td>52 (10-160)</td>
</tr>
<tr>
<td>São Simão Alto</td>
<td>58 (28-130)</td>
<td>41 (11-110)</td>
</tr>
<tr>
<td>Teles Pires</td>
<td>61 (29-140)</td>
<td>43 (10-120)</td>
</tr>
</tbody>
</table>
6.4.5 Sensitivity Analysis: effect of including data outlier from Samuel

Based on the statistical analysis of the data and the weather conditions reported during the sampling, we considered the diffusion point from Samuel reservoir at 16 years old an outlier. The goal of this section is to evaluate the influence of this outlier in our results and conclusions.

The inclusion of the outlier changes the best distribution for reservoir surface CO$_2$ emissions for both model selection criteria (Akaike information criterion and Bayesian information criterion). Instead of the Rayleigh distribution (scale parameter: 4589.8), the best distribution is a log-logistic distribution (parameters: location = 8.53, scale = 0.46). Table S29 shows the effect of the inclusion of this outlier in total CO$_2$ emissions. As expected, the inclusion of the outlier and the change in the probability distribution affects our estimates, because the log-logistic distribution is more skewed to the right than the Rayleigh distribution. As a result, the main effect of the shift happens to the upper bound confidence interval. The effect in the upper bound is only substantial for Cachoeira do Cai, Cachoeira do Caldeirão, Cachoeira dos Patos and Sinop.
Table S29 - Sensitivity analysis of the impact of Samuel outliers in total CO₂ emissions. Simulation results over a period of 100 years (in Tg of C): mean, median and 95% Confidence Interval (2.5% - 97.5%).

<table>
<thead>
<tr>
<th></th>
<th>Without Samuel at 16 years old</th>
<th>With Samuel at 16 years old</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Median</td>
</tr>
<tr>
<td>Belo Monte</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>Bem Querer</td>
<td>29</td>
<td>22</td>
</tr>
<tr>
<td>Cachoeira do Caí</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td>Cachoeira do Caldeirão</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Cachoeira dos Patos</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Colíder</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Ferreira Gomes</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Jamanxim</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Jatobá</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>Jirau</td>
<td>36</td>
<td>34</td>
</tr>
<tr>
<td>Marabá</td>
<td>45</td>
<td>33</td>
</tr>
<tr>
<td>Salto Augusto de Baixo</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Santo Antônio</td>
<td>28</td>
<td>27</td>
</tr>
<tr>
<td>São Luís do Tapajos</td>
<td>25</td>
<td>22</td>
</tr>
<tr>
<td>São Manoel</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>São Simão Alto</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>Sinop</td>
<td>24</td>
<td>23</td>
</tr>
<tr>
<td>Teles Pires</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

Table S30 and Table S31 show the effect of the outlier inclusion in total net reservoir emissions and emission factors, respectively. The results confirm that the only significant effect in the emissions output happens only to the upper bound 95% confidence interval. The outlier inclusion does not change our conclusions about the level of emissions from each reservoir compared to thermal power plants.
Table S30 - Sensitivity analysis of the impact of Samuel outliers in total net reservoir GHG emissions. Simulation results over a period of 100 years (in Tg of CO₂eq): average, median and 95% Confidence Interval (2.5% - 97.5%).

<table>
<thead>
<tr>
<th>Location</th>
<th>Without Samuel at 16 years old</th>
<th>With Samuel at 16 years old</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Median</td>
</tr>
<tr>
<td>Belo Monte</td>
<td>150</td>
<td>123</td>
</tr>
<tr>
<td>Bem Querer</td>
<td>208</td>
<td>171</td>
</tr>
<tr>
<td>Cachoeira do Caí</td>
<td>392</td>
<td>393</td>
</tr>
<tr>
<td>Cachoeira do Caldeirão</td>
<td>14</td>
<td>12</td>
</tr>
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### Table S31 - Sensitivity analysis of the impact of Samuel outliers in the emission factors. Simulation results over a period of 100 years (in Tg of CO$_2$eq): average, median and 95% Confidence Interval (2.5% - 97.5%).

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### 6.4.6 Energy density vs. emission factor

Figures S13 and S14 confirm that the relationship between energy density and emissions factors is strong and negatively correlated. The use of both approaches provides a reasonable range of values for comparing future reservoir emissions in the Amazon with those from other sources of electricity generation.
Figure S13 – Average emission factor (over 100 years period, GWP -34) plotted against energy density from each studied reservoirs. Number Identification: 1 - C. do Cai, 2 - C. dos Patos, 3 – Jamanxim, 4 – Sinop, 5 - Belo Monte, 6 - Bem Querer, 7 - C. do Caldeirão, 8 – Colíder, 9 - F. Gomes, 10 – Jatobá, 11 – Jirau , 12 – Marabá, 13 - Salto A. de Baixo, 14 - Santo Antônio, 15 - São L. do Tapajos, 16 - São Manoel, 17 - São Simão Alto, 18 - Teles Pires.
Figure S14 – Average emission factor (over 20 years period, GWP -86) plotted against energy density from each studied reservoirs. Number Identification: 1 - C. do Caí, 2 - C. dos Patos, 3 – Jamanxim, 4 – Sinop, 5 - Belo Monte, 6 - Bem Querer, 7 - C. do Caldeirão, 8 – Colíder, 9 - F. Gomes, 10 – Jatobá, 11 – Jirau , 12 – Marabá, 13 - Salto A. de Baixo, 14 - Santo Antônio, 15 - São L. do Tapajos, 16 - São Manoel, 17 - São Simão Alto, 18 - Teles Pires.

6.4.7 Climate change and land used change uncertainty

Climate change and deforestation in the Amazon are factors that may affect atmospheric and surface conditions in the future, which then would impact GHG emissions from reservoirs. Amazon precipitation pattern changes are considered one of the main impacts from land use change and global warming (Malhi et al. 2008). Precipitation controls discharge variability of
the Amazon rivers (Villar et al. 2009), which affects limnological conditions of reservoirs. For instance, lower discharges increase reservoir RT, which is positively correlated to emissions (Pacheco et al. 2015; Abril et al. 2005). Changes in flow patterns also affect energy production, and consequently, the emission factor of the hydropower projects. For example, projections for Belo Monte reservoir shows that land use change in the Xingu Basin reduce flows patterns, and expected energy production decreases by 5% to 40% (Stickler, Coe & Costa 2013).

IPCC projections indicate temperature increase in South America are very likely to occur, with greatest warming projected in the southern Amazon region (IPCC 2013). Less rainfall is very likely to also occur in the eastern Amazon region during the dry season, but the effect in the rainy season is still very uncertain (IPCC 2013; Joetzjer et al. 2013). Regarding extremes precipitations, there is a high likelihood of the intensification of these events (IPCC 2013). The impacts of climate change on freshwater systems will likely 1) increase water temperatures and eutrophication, 2) decrease dissolved-oxygen levels, and 3) strengthen stratification (Roland, Huszar & Farjalla 2012).

Deforestation also affects Amazon hydrometeorology (Baidya Roy 2002; Costa & Pires 2009; Wang, Chagnon & Williams 2009), and can itself be a factor of climate change and a positive feedback on externally forced climate change (Malhi et al. 2008). Shifts in the regional climate patterns can influence reservoir emissions by changing the heat balance and surface mixed layer dynamics of hydroelectric reservoirs (Curtarelli et al. 2014). Any modification on precipitation and wind patterns can also affect emissions, as they are important factors to define gas exchange flux variability (Abril et al. 2005). Additionally, land use change from forest to agriculture or urban areas can increase eutrophication and cause a reversal in the role played by oligotrophic systems by increasing atmospheric C sequestration as sediment and dissolved
organic C (Pacheco, Roland & Downing 2014). Finally, hydroelectric development can promote indirect deforestation, which increases emissions related to the projects (Fearnside 2015a).

At this point, we are unable to quantify the magnitude of future climate and land use change on our estimates. The direction of most of the effects, however, indicates that these factors will likely contribute to the increase in emission factors from hydropower plants in the Amazon.
References


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7. APPENDIX B: CHAPTER 3
7.1 Introduction

This chapter includes details about the data and outcomes described in Chapter 3, along with additional results and analyses. First, we provide a more detailed description of the data used in the study, such as the characteristics of the hydropower plants and additional statistics about the variables of interest. Second, we employ various methods to assess the robustness of the main findings of Chapter 3, such as alternative assumptions about clustering and model specification. Third, we present a complementary assessment of the heterogeneity of the economic impacts of hydropower development by some critical characteristics, such as project size (installed capacity) and plant ownership (utility or industry).

7.2 Data

7.2.1 Hydropower plants built between 1991 and 2010

Table S1 characterizes the main features of the 56 hydropower plants built in Brazil between 1991 and 2010 that were used in the study. The projects include a total of 23 gigawatts of installed capacity and 10,000 km2 of reservoir area. We identified the counties affected by power plants listed on Table 1 using the water resources compensation policy database organized by the Brazilian Electricity Regulatory Agency (ANEEL – Agencia Nacional de Energia Eletrica, 2015b). The reservoirs from these hydropower plants affected 242 counties based on the 2010 county territory map. Annex C1 contains the list of the control counties.
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<th>Reservoir Area (km²)</th>
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<th>Beginning of Operation (First turbine)</th>
<th>Owner</th>
<th>Industry or Utility</th>
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</table>
7.2.2 Undeveloped hydropower plants: control group

The regulatory process to develop power plants in Brazil can be summarized by three major stages: 1) watershed master plan, 2) viability study, and 3) basic design. Each stage adds complexity to the level of details in the engineering and environmental studies. ANEEL assesses, manages and approves those studies, and makes part of this information publicly available (ANEEL, 2015a). We used hydropower plants that were not built yet to identify our group of control counties. Table S2 contains the list of undeveloped hydropower plants sites. The reasons why some hydropower projects are still undeveloped include: lack of financial viability, environmental and social restrictions, legal or regulatory issues, or project still completing different stages of the regulatory process. For example, in 2001, a private company obtained the legal rights to build the Murta project, a 120 MW power plant sitet in the state of Minas Gerais. The project is still under discussion because many households would need to be relocated out of the area that would be flooded by the reservoir. Another example is the Garabi project that has been “under development” since 1970. This project is on the border of Brazil and Argentina, a
condition that adds complexity to the regulatory process and project development because of the need of agreement between the two countries. In the main model, we include as counterfactuals only the counties within a distance of 200 kilometers from our treatment group.

Table S5: Undeveloped hydropower plants used to identify control counties

<table>
<thead>
<tr>
<th>ID</th>
<th>Name</th>
<th>Installed Capacity (kW)</th>
<th>ID</th>
<th>Name</th>
<th>Installed Capacity (kW)</th>
<th>ID</th>
<th>Name</th>
<th>Installed Capacity (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Água Branca</td>
<td>73,000</td>
<td>45</td>
<td>Encantado</td>
<td>36,200</td>
<td>90</td>
<td>Pedra Branca</td>
<td>320,000</td>
</tr>
<tr>
<td>2</td>
<td>Água Clara</td>
<td>32,450</td>
<td>46</td>
<td>Ercilândia</td>
<td>96,600</td>
<td>91</td>
<td>Perdida 2</td>
<td>48,000</td>
</tr>
<tr>
<td>3</td>
<td>Água Limpa</td>
<td>320,000</td>
<td>47</td>
<td>Escada Grande</td>
<td>41,000</td>
<td>92</td>
<td>Pompeu</td>
<td>209,100</td>
</tr>
<tr>
<td>4</td>
<td>Águas Lindas</td>
<td>40,000</td>
<td>48</td>
<td>Escaramuça</td>
<td>50,000</td>
<td>93</td>
<td>Ponte Indaiá</td>
<td>51,400</td>
</tr>
<tr>
<td>5</td>
<td>A38PA100</td>
<td>177,800</td>
<td>49</td>
<td>Escura</td>
<td>75,000</td>
<td>94</td>
<td>Porto Ferreira</td>
<td>49,300</td>
</tr>
<tr>
<td>6</td>
<td>Almenara</td>
<td>100,000</td>
<td>50</td>
<td>Espigão Preto</td>
<td>34,000</td>
<td>95</td>
<td>Porto Guarita</td>
<td>47,350</td>
</tr>
<tr>
<td>7</td>
<td>Alta Floresta</td>
<td>127,800</td>
<td>51</td>
<td>Estreito</td>
<td>56,000</td>
<td>96</td>
<td>Pouso Alto</td>
<td>76,000</td>
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<td>Apertados</td>
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<td>52</td>
<td>Formoso</td>
<td>342,000</td>
<td>97</td>
<td>Quebra Remo</td>
<td>267,800</td>
</tr>
<tr>
<td>9</td>
<td>Araguainha</td>
<td>48,000</td>
<td>53</td>
<td>Foz do Atalaia</td>
<td>72,000</td>
<td>98</td>
<td>Riacho Seco</td>
<td>276,000</td>
</tr>
<tr>
<td>10</td>
<td>Araguai</td>
<td>960,000</td>
<td>54</td>
<td>Foz do Piquiri</td>
<td>101,200</td>
<td>99</td>
<td>Ribeiro Goncalves</td>
<td>113,000</td>
</tr>
<tr>
<td>11</td>
<td>Arroio do Meio 30.0</td>
<td>68,600</td>
<td>55</td>
<td>Foz do xaxim</td>
<td>63,200</td>
<td>100</td>
<td>Rio Sono Baixo</td>
<td>56,700</td>
</tr>
<tr>
<td>12</td>
<td>Bambu I</td>
<td>84,000</td>
<td>56</td>
<td>Galileia</td>
<td>238,000</td>
<td>101</td>
<td>Rochedo II</td>
<td>70,000</td>
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<tr>
<td>13</td>
<td>Bananeiras</td>
<td>200,000</td>
<td>57</td>
<td>Garabi</td>
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<td>102</td>
<td>Roncador</td>
<td>134,000</td>
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<td>67,000</td>
<td>58</td>
<td>Guatambó</td>
<td>34,500</td>
<td>103</td>
<td>Sáo Cristóvão</td>
<td>47,820</td>
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<tr>
<td>15</td>
<td>Barra do Claro</td>
<td>61,000</td>
<td>59</td>
<td>Ilha São Pedro</td>
<td>131,000</td>
<td>104</td>
<td>Sáo Jerônimo</td>
<td>340,000</td>
</tr>
<tr>
<td>16</td>
<td>Barretos</td>
<td>46,500</td>
<td>60</td>
<td>Iraí</td>
<td>330,000</td>
<td>105</td>
<td>Sáo Joao</td>
<td>60,000</td>
</tr>
<tr>
<td>17</td>
<td>Bem Querer J1A</td>
<td>708,400</td>
<td>61</td>
<td>Itaocara I</td>
<td>150,000</td>
<td>106</td>
<td>Sáo Manuel</td>
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<td>Berimbau</td>
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<td>62</td>
<td>Itapiranga</td>
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<td>107</td>
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<td>57,000</td>
</tr>
<tr>
<td>19</td>
<td>Biboca</td>
<td>57,000</td>
<td>63</td>
<td>Jamanxim</td>
<td>881,000</td>
<td>108</td>
<td>Sáo Roque</td>
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</tr>
<tr>
<td>20</td>
<td>Boaventura</td>
<td>32,100</td>
<td>64</td>
<td>Januária</td>
<td>180,000</td>
<td>109</td>
<td>Saco</td>
<td>114,000</td>
</tr>
<tr>
<td>21</td>
<td>Bois 12</td>
<td>74,900</td>
<td>65</td>
<td>Jenipapo</td>
<td>96,300</td>
<td>110</td>
<td>Salto Ariranha</td>
<td>36,670</td>
</tr>
<tr>
<td>22</td>
<td>Bois 13</td>
<td>64,500</td>
<td>66</td>
<td>Jequitinhonha</td>
<td>101,400</td>
<td>111</td>
<td>Salto Duran</td>
<td>36,100</td>
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<tr>
<td>23</td>
<td>Bom Retiro</td>
<td>45,000</td>
<td>67</td>
<td>JRN-277</td>
<td>1,248,000</td>
<td>112</td>
<td>Santa Isabel</td>
<td>108,700</td>
</tr>
<tr>
<td>24</td>
<td>Brejão</td>
<td>75,000</td>
<td>68</td>
<td>JRN-466</td>
<td>510,000</td>
<td>113</td>
<td>Santa Rita</td>
<td>61,000</td>
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<tr>
<td>25</td>
<td>BUR-039</td>
<td>37,500</td>
<td>69</td>
<td>JRN-530</td>
<td>415,000</td>
<td>114</td>
<td>Santo Antônio</td>
<td>84,300</td>
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<td>Cachoeirão</td>
<td>64,000</td>
<td>70</td>
<td>JRN-577</td>
<td>225,000</td>
<td>115</td>
<td>Santo Hipólito</td>
<td>95,000</td>
</tr>
<tr>
<td>27</td>
<td>Cachoeira</td>
<td>63,000</td>
<td>71</td>
<td>JRN-720</td>
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<td>116</td>
<td>Saudade</td>
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<tr>
<td>28</td>
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<td>72</td>
<td>JUI-048</td>
<td>53,000</td>
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<td>Serra Quebrada</td>
<td>1,328,000</td>
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<td>29</td>
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<td>Lagoinha</td>
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<td>118</td>
<td>Sinop</td>
<td>775,000</td>
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<tr>
<td>30</td>
<td>Cachoeira Galinha</td>
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<td>74</td>
<td>Lajeado III</td>
<td>46,800</td>
<td>119</td>
<td>Sucuri</td>
<td>38,000</td>
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<td>31</td>
<td>Cachoeira Velha</td>
<td>81,000</td>
<td>75</td>
<td>Limoeiro</td>
<td>142,000</td>
<td>120</td>
<td>Sumauma</td>
<td>458,200</td>
</tr>
<tr>
<td>32</td>
<td>Cachoeirinha</td>
<td>45,000</td>
<td>76</td>
<td>Lua Cheia</td>
<td>103,000</td>
<td>121</td>
<td>Tabajara</td>
<td>350,000</td>
</tr>
<tr>
<td>33</td>
<td>Cambuci</td>
<td>50,000</td>
<td>77</td>
<td>Magessi</td>
<td>53,000</td>
<td>122</td>
<td>Taboa</td>
<td>98,000</td>
</tr>
<tr>
<td>34</td>
<td>Canto do Rio</td>
<td>44,000</td>
<td>78</td>
<td>Marabi</td>
<td>2,160,000</td>
<td>123</td>
<td>Telemaco Borba</td>
<td>118,000</td>
</tr>
<tr>
<td>35</td>
<td>Cantu</td>
<td>36,700</td>
<td>79</td>
<td>Maranhão</td>
<td>125,000</td>
<td>124</td>
<td>Tibagi Montante</td>
<td>32,000</td>
</tr>
</tbody>
</table>
7.2.3 Precipitation and air temperature data

Annual precipitation and air temperature data for each county was estimated using the global precipitation and temperature series developed by Willmott & Matsuura from the University of Delaware (Willmott & Matsuura, 2015). The database contains time series (1900-2010) of global terrestrial air temperature and precipitation at a spatial grid resolution of 0.5x0.5 degree. We defined the county value based on the smallest Euclidian distance from the county to the precipitation and temperature grid.

7.2.4 Tax data characteristics

This section describes the characteristics of the variables used to describe county public revenues: total public revenue, services tax – ISS, state transfers – ICMS, and federal transfers FPM.

The first indicator is the total income of the county (Public revenue), which represents on average 95% of the total revenues for a county, excluding capital revenues (e.g. credit operations and disposal of assets). The second public budget indicator is the local service tax (Imposto Sobre Serviços – ISS, in Portuguese). Although the ISS corresponds to a small fraction of the
budget for most counties (around 3% of the total public revenues), the tax is a very good proxy
to evaluate the effect of the construction and operation of hydropower plants on the local
economy, because it is a direct measure of the level of economic activity in the services sector.
The third indicator is the Brazilian state excise tax (Imposto sobre Circulação de Mercadorias e
Serviços – ICMS, in Portuguese). The ICMS is paid over the purchase of goods and
transportation and communication services, including electricity. On average, ICMS transfers
accounted for 20% to 30% of a county’s income between 1991 and 2010. The last indicator is a
federal transfer to the counties called “counties’ participation fund” (Fundo de Participação dos
Municípios – FPM, in Portuguese). The share received by each county is a function of county
population and the state where the county is located. The FPM is one of the most important
sources of income for counties, and its proportion of the total revenues ranges from 30% to 40%
(averages from 1991 to 2010). Most of the counties in Brazil depend heavily on state and federal
transfers, representing on average 85% of their total public revenues.

7.3 Socioeconomic Indicators – Summary Statistics

Table S3 presents the statistical summary of the socioeconomic indicators according to
treated groups (A and B) and control group in 1991. Treated group A represents counties with
hydropower plants built between 1991 and 2000 and treated group B represents counties with
hydropower plants built between 2000 and 2010. Table 2 shows that control and treated groups
have similar statistics for some indicators (e.g. education and teenage pregnancy) but different
statistics for others (e.g. longevity and percentage of households with access to piped water).
Because of this heterogeneity, we include covariates in the regression to be able to control for observables and time-invariant unobservables.

### Table S3 - Socioeconomic indicator sample statistics

<table>
<thead>
<tr>
<th>Socioeconomic indicators (1991)</th>
<th>Group A (n=46)</th>
<th>Group B (n=101)</th>
<th>Control Group (n=106)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Standard deviation</td>
<td>Mean</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>Education</td>
<td>0.21</td>
<td>0.07</td>
<td>0.18</td>
</tr>
<tr>
<td>Longevity</td>
<td>0.57</td>
<td>0.05</td>
<td>0.54</td>
</tr>
<tr>
<td>Income</td>
<td>0.69</td>
<td>0.06</td>
<td>0.67</td>
</tr>
<tr>
<td>% of households with access to electricity</td>
<td>83</td>
<td>15</td>
<td>70</td>
</tr>
<tr>
<td>% of households with access to piped water</td>
<td>73</td>
<td>19</td>
<td>58</td>
</tr>
<tr>
<td>% teenager pregnancy</td>
<td>3.1</td>
<td>2.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Number of HIV cases</td>
<td>3.9</td>
<td>16.1</td>
<td>3.4</td>
</tr>
</tbody>
</table>

#### 7.4 Sensitivity Analysis

To evaluate the robustness of our main findings, we implemented a sensitivity analysis consisting of two parts. First, we evaluated the effect of different clustering alternatives on the variance of estimated parameters. We assessed the results for three different clustering assumptions: no clustering, clustering by county, and clustering by county and hydropower plant (Model 1 from Chapter 3). Second, we assessed the effect on the regression estimates of (i) relaxing the restriction of using only counties with unexplored hydropower potential as controls, and (ii) excluding and including covariates from our main model specification. The sensitivity analysis confirms that the event-time dummy results from the main model (Model 1) are stable under alternative conditions.
7.4.1. Gross domestic product

Table S4 to Table S7 present the regression results for total GDP and its subaccounts (industry, agriculture and services). The column called “Main model” describes the results presented in the main document (Model 1). Columns A and B represent the results of distinct clustering assumptions and the last three columns present the coefficients assuming alternative conditions: 1) relaxing the restriction of using only counties with hydropower plants that didn’t materialize as controls, 2) without covariates (temperature, precipitation, royalties and state GDP, and 3) adding another covariate (population).

Overall, the estimates of the sensitivity analysis are qualitatively similar. Regarding the clustering alternatives, it is possible to see that, in general, the standard errors follow a pattern:

Clustered by county and hydropower plants > Clustered by county > No clustering

This result is expected given that failure to control for within-cluster error correlation can lead to misleadingly small standard errors, and consequent misleadingly narrow confidence intervals, large t-statistics, and low p-values (Cameron & Miller, 2015).

Regarding the alternative condition “1” (where we relax the restriction of using only counties with unexplored hydropower potential as controls), the outcomes indicate that the failure to control for natural advantages and siting decisions tends to result in a slight overestimation of the average coefficients, consistent with other findings in the literature (e.g. Severnini, 2014). Furthermore, the covariates exclusion (condition “2”) and inclusion (condition “3”) do not result in major effects for the event-time dummy coefficients (ED) and standard
errors. We did not add population as a covariate in the main model because of the potential feedbacks between economic output and population that could bias the ED coefficients.
Table S5: Sensitivity Analysis – regression results (dependent variable Total GDP)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1) Relaxing the restriction of using only counties with unexplored hydropower potential as controls</td>
</tr>
<tr>
<td></td>
<td>Main Model</td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
</tr>
<tr>
<td>EDminus5</td>
<td>0.028 (0.045)</td>
</tr>
<tr>
<td>EDminus4</td>
<td>0.004 (0.028)</td>
</tr>
<tr>
<td>EDminus3</td>
<td>-0.021 (0.031)</td>
</tr>
<tr>
<td>EDminus2</td>
<td>-0.037 (0.033)</td>
</tr>
<tr>
<td>EDzero</td>
<td>-0.011 (0.031)</td>
</tr>
<tr>
<td>EDplus1</td>
<td>-0.005 (0.038)</td>
</tr>
<tr>
<td>EDplus2</td>
<td>0.040 (0.040)</td>
</tr>
<tr>
<td>EDplus3</td>
<td>0.099*** (0.042)</td>
</tr>
<tr>
<td>EDplus4</td>
<td>0.091** (0.037)</td>
</tr>
<tr>
<td>EDplus5</td>
<td>0.092*** (0.032)</td>
</tr>
<tr>
<td>EDplus6</td>
<td>0.065** (0.032)</td>
</tr>
<tr>
<td>EDplus7</td>
<td>0.060* (0.031)</td>
</tr>
<tr>
<td>EDplus8</td>
<td>0.050 (0.031)</td>
</tr>
<tr>
<td>EDplus9</td>
<td>0.045 (0.029)</td>
</tr>
<tr>
<td>EDplus10</td>
<td>0.046 (0.031)</td>
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<tr>
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<td>0.041 (0.030)</td>
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<tr>
<td>EDplus12</td>
<td>0.020 (0.026)</td>
</tr>
<tr>
<td>EDplus13</td>
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<tr>
<td>EDplus14</td>
<td>0.023 (0.015)</td>
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<tr>
<td>EDplus15</td>
<td>0.045*** (0.016)</td>
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<tr>
<td>log (state GDP)</td>
<td>0.177* (0.101)</td>
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<tr>
<td>Itaipu royalties</td>
<td>-0.001 (0.002)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>-0.000** (0.000)</td>
</tr>
<tr>
<td>Temperature</td>
<td>-0.014 (0.010)</td>
</tr>
<tr>
<td>Population</td>
<td>0.000 (0.000)</td>
</tr>
</tbody>
</table>

Notes: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.
Table S5: Sensitivity Analysis – regression results (dependent variable Industry GDP)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
</tr>
</thead>
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<tr>
<td></td>
<td>1) Relaxing the restriction of using only counties with unexplored hydropower potential as controls</td>
</tr>
<tr>
<td></td>
<td>Main Model</td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
</tr>
<tr>
<td>EDminus5</td>
<td>0.249*** (0.125)</td>
</tr>
<tr>
<td>EDminus4</td>
<td>0.209* (0.121)</td>
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<tr>
<td>EDminus3</td>
<td>-0.057 (0.177)</td>
</tr>
<tr>
<td>EDminus2</td>
<td>0.059 (0.141)</td>
</tr>
<tr>
<td>EDzero</td>
<td>0.075 (0.113)</td>
</tr>
<tr>
<td>EDplus1</td>
<td>0.044 (0.166)</td>
</tr>
<tr>
<td>EDplus2</td>
<td>0.202 (0.133)</td>
</tr>
<tr>
<td>EDplus3</td>
<td>0.318** (0.128)</td>
</tr>
<tr>
<td>EDplus4</td>
<td>0.326*** (0.118)</td>
</tr>
<tr>
<td>EDplus5</td>
<td>0.306*** (0.087)</td>
</tr>
<tr>
<td>EDplus6</td>
<td>0.266*** (0.082)</td>
</tr>
<tr>
<td>EDplus7</td>
<td>0.245*** (0.073)</td>
</tr>
<tr>
<td>EDplus8</td>
<td>0.265*** (0.080)</td>
</tr>
<tr>
<td>EDplus9</td>
<td>0.165*** (0.061)</td>
</tr>
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<td>EDplus10</td>
<td>0.141** (0.059)</td>
</tr>
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<td>EDplus11</td>
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<td>EDplus12</td>
<td>0.122** (0.059)</td>
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<td>EDplus13</td>
<td>0.090* (0.047)</td>
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<td>EDplus14</td>
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</tr>
<tr>
<td>EDplus15</td>
<td>0.106** (0.051)</td>
</tr>
<tr>
<td>log (state GDP)</td>
<td>0.740** (0.322)</td>
</tr>
<tr>
<td>Itaipu royalties</td>
<td>-0.018** (0.009)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>-0.000*** (0.000)</td>
</tr>
<tr>
<td>Temperature</td>
<td>-0.080** (0.040)</td>
</tr>
<tr>
<td>Population</td>
<td>0.000 (0.000)</td>
</tr>
</tbody>
</table>

Notes: ***Significant at the 1 percent level; **Significant at the 5 percent level; * Significant at the 10 percent level.
Table S7: Sensitivity Analysis – regression results (dependent variable Services GDP)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Model</td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
</tr>
<tr>
<td>EDminus5</td>
<td>0.049 (0.035)</td>
</tr>
<tr>
<td>EDminus4</td>
<td>0.019 (0.025)</td>
</tr>
<tr>
<td>EDminus3</td>
<td>-0.010 (0.026)</td>
</tr>
<tr>
<td>EDminus2</td>
<td>0.004 (0.020)</td>
</tr>
<tr>
<td>EDzero</td>
<td>0.030 (0.025)</td>
</tr>
<tr>
<td>EDplus1</td>
<td>0.022 (0.027)</td>
</tr>
<tr>
<td>EDplus2</td>
<td>0.031 (0.027)</td>
</tr>
<tr>
<td>EDplus3</td>
<td>0.070** (0.029)</td>
</tr>
<tr>
<td>EDplus4</td>
<td>0.059** (0.028)</td>
</tr>
<tr>
<td>EDplus5</td>
<td>0.040 (0.025)</td>
</tr>
<tr>
<td>EDplus6</td>
<td>0.028 (0.025)</td>
</tr>
<tr>
<td>EDplus7</td>
<td>0.037 (0.029)</td>
</tr>
<tr>
<td>EDplus8</td>
<td>0.020 (0.025)</td>
</tr>
<tr>
<td>EDplus9</td>
<td>0.026 (0.029)</td>
</tr>
<tr>
<td>EDplus10</td>
<td>0.032 (0.030)</td>
</tr>
<tr>
<td>EDplus11</td>
<td>0.022 (0.028)</td>
</tr>
<tr>
<td>EDplus12</td>
<td>0.028 (0.025)</td>
</tr>
<tr>
<td>EDplus13</td>
<td>0.002 (0.022)</td>
</tr>
<tr>
<td>EDplus14</td>
<td>0.002 (0.018)</td>
</tr>
<tr>
<td>EDplus15</td>
<td>0.011 (0.014)</td>
</tr>
<tr>
<td>log (state GDP)</td>
<td>0.040 (0.078)</td>
</tr>
<tr>
<td>Itaipu royalties</td>
<td>0.002 (0.002)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>-0.000*** (0.000)</td>
</tr>
<tr>
<td>Temperature</td>
<td>-0.002 (0.007)</td>
</tr>
<tr>
<td>Population</td>
<td>0.000 (0.000)</td>
</tr>
</tbody>
</table>

Notes: **Significant at the 1 percent level;***Significant at the 5 percent level;*Significant at the 10 percent level.
## Table S8: Sensitivity Analysis – regression results (dependent variable Agriculture GDP)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1) Relaxes the restriction of using only counties with unexplored hydropower potential as controls</td>
</tr>
<tr>
<td></td>
<td>Main Model</td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specification alternatives</th>
<th>1) Relaxes the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>2) Without covariates (temperature, precipitation, royalties and state GDP)</th>
<th>3) Adding a covariate (population)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Model</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>EDminus5</td>
<td>-0.107 (0.069)</td>
<td>-0.107*** (0.046)</td>
<td>-0.107*** (0.049)</td>
</tr>
<tr>
<td>EDminus4</td>
<td>-0.127** (0.058)</td>
<td>-0.127*** (0.046)</td>
<td>-0.127*** (0.043)</td>
</tr>
<tr>
<td>EDminus3</td>
<td>-0.026 (0.054)</td>
<td>-0.026 (0.044)</td>
<td>-0.026 (0.040)</td>
</tr>
<tr>
<td>EDminus2</td>
<td>-0.059 (0.058)</td>
<td>-0.059 (0.037)</td>
<td>-0.020065</td>
</tr>
<tr>
<td>EDzero</td>
<td>-0.059 (0.045)</td>
<td>-0.059** (0.030)</td>
<td>-0.001888</td>
</tr>
<tr>
<td>EDplus1</td>
<td>-0.081* (0.047)</td>
<td>-0.081** (0.032)</td>
<td>-0.081*** (0.030)</td>
</tr>
<tr>
<td>EDplus2</td>
<td>-0.047 (0.047)</td>
<td>-0.047 (0.031)</td>
<td>-0.047 (0.029)</td>
</tr>
<tr>
<td>EDplus3</td>
<td>-0.046 (0.055)</td>
<td>-0.046 (0.037)</td>
<td>-0.046 (0.028)</td>
</tr>
<tr>
<td>EDplus4</td>
<td>-0.089* (0.047)</td>
<td>-0.089*** (0.034)</td>
<td>-0.089*** (0.027)</td>
</tr>
<tr>
<td>EDplus5</td>
<td>-0.083* (0.046)</td>
<td>-0.083*** (0.033)</td>
<td>-0.083*** (0.029)</td>
</tr>
<tr>
<td>EDplus6</td>
<td>-0.105** (0.043)</td>
<td>-0.105*** (0.033)</td>
<td>-0.105*** (0.028)</td>
</tr>
<tr>
<td>EDplus7</td>
<td>-0.086* (0.052)</td>
<td>-0.086** (0.038)</td>
<td>-0.086** (0.028)</td>
</tr>
<tr>
<td>EDplus8</td>
<td>-0.09* (0.047)</td>
<td>-0.090*** (0.031)</td>
<td>-0.090*** (0.025)</td>
</tr>
<tr>
<td>EDplus9</td>
<td>-0.047 (0.051)</td>
<td>-0.047 (0.033)</td>
<td>-0.001222</td>
</tr>
<tr>
<td>EDplus10</td>
<td>-0.019 (0.048)</td>
<td>-0.019 (0.033)</td>
<td>-0.019 (0.028)</td>
</tr>
<tr>
<td>EDplus11</td>
<td>0.021 (0.044)</td>
<td>0.021 (0.032)</td>
<td>0.021 (0.029)</td>
</tr>
<tr>
<td>EDplus12</td>
<td>-0.077 (0.055)</td>
<td>-0.077** (0.035)</td>
<td>-0.077*** (0.030)</td>
</tr>
<tr>
<td>EDplus13</td>
<td>-0.091** (0.038)</td>
<td>-0.091** (0.036)</td>
<td>-0.091*** (0.033)</td>
</tr>
<tr>
<td>EDplus14</td>
<td>-0.007 (0.042)</td>
<td>-0.007 (0.033)</td>
<td>-0.007 (0.032)</td>
</tr>
<tr>
<td>EDplus15</td>
<td>0.044 (0.039)</td>
<td>0.044 (0.031)</td>
<td>0.044 (0.035)</td>
</tr>
<tr>
<td>log (state GDP)</td>
<td>0.186 (0.167)</td>
<td>0.186** (0.091)</td>
<td>0.186*** (0.053)</td>
</tr>
<tr>
<td>Itaipu royalties</td>
<td>-0.003 (0.004)</td>
<td>-0.003 (0.003)</td>
<td>-0.003 (0.004)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>-0.000** (0.000)</td>
<td>-0.000*** (0.000)</td>
<td>-0.000*** (0.000)</td>
</tr>
<tr>
<td>Temperature</td>
<td>-0.000 (0.014)</td>
<td>-0.000 (0.011)</td>
<td>-0.000 (0.010)</td>
</tr>
<tr>
<td>Population</td>
<td>0.000 (0.000)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.4.2. Tax revenues

Table S8 to S11 present the detailed regression results for the total public revenues and its subaccounts (Services tax - ISS, State transfers - ICMS, and Federal transfers - FPM). Overall, the conclusions reported for the GDP sensitivity hold for the tax revenues sensitivities. A minor difference occurs for condition “1” (where we relax the restriction of using only counties with hydropower potential that didn’t materialize as controls), where instead of an overestimation, the outcomes are sometimes underestimated in relation to the main model event-time dummy coefficients. However, the results are still qualitative similar.
Table S6: Sensitivity Analysis – regression results (dependent variable Public revenues)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1) Relaxing the restriction of using only counties with unexplored hydropower potential as controls</td>
</tr>
<tr>
<td></td>
<td>Main Model</td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td></td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td></td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
</tr>
</tbody>
</table>

| EDminus5 | 0.008 (0.021) | 0.008 (0.020) | 0.008 (0.021) | 0.011 (0.022) | 0.008 (0.020) | 0.010 (0.021) |
| EDminus4 | -0.005 (0.020) | -0.005 (0.020) | -0.005 (0.020) | -0.003 (0.022) | -0.005 (0.021) | -0.005 (0.020) |
| EDminus3 | -0.003 (0.021) | -0.003 (0.020) | -0.003 (0.021) | -0.009 (0.022) | -0.003 (0.021) | -0.003 (0.021) |
| EDminus2 | 0.015 (0.021) | 0.015 (0.020) | 0.015 (0.020) | 0.000 (0.022) | 0.015 (0.021) | 0.014 (0.021) |
| EDzero | 0.032 (0.023) | 0.032 (0.023) | 0.032** (0.018) | 0.027 (0.018) | 0.032 (0.024) | 0.033 (0.025) |
| EDplus1 | 0.057** (0.026) | 0.057** (0.026) | 0.057*** (0.017) | 0.034* (0.018) | 0.057** (0.026) | 0.058** (0.026) |
| EDplus2 | 0.046 (0.028) | 0.046* (0.027) | 0.046*** (0.018) | 0.014 (0.018) | 0.046* (0.028) | 0.046* (0.028) |
| EDplus3 | 0.059** (0.028) | 0.059** (0.027) | 0.059*** (0.018) | 0.028 (0.018) | 0.059** (0.028) | 0.058** (0.027) |
| EDplus4 | 0.045 (0.028) | 0.045* (0.027) | 0.045** (0.018) | 0.005 (0.019) | 0.045 (0.028) | 0.045 (0.028) |
| EDplus5 | 0.065** (0.027) | 0.065** (0.026) | 0.065*** (0.019) | 0.021 (0.019) | 0.065** (0.027) | 0.062** (0.027) |
| EDplus6 | 0.063** (0.027) | 0.063** (0.026) | 0.063*** (0.019) | 0.024 (0.019) | 0.063** (0.028) | 0.061** (0.027) |
| EDplus7 | 0.080*** (0.024) | 0.080*** (0.023) | 0.080*** (0.020) | 0.036* (0.020) | 0.080*** (0.023) | 0.078*** (0.024) |
| EDplus8 | 0.093*** (0.025) | 0.093*** (0.024) | 0.093*** (0.021) | 0.045** (0.021) | 0.093*** (0.024) | 0.092*** (0.025) |
| EDplus9 | 0.074*** (0.026) | 0.074*** (0.025) | 0.074*** (0.021) | 0.022 (0.021) | 0.074** (0.029) | 0.074** (0.026) |
| EDplus10 | 0.044* (0.026) | 0.044* (0.026) | 0.044* (0.023) | -0.008 (0.023) | 0.044* (0.026) | 0.048* (0.026) |
| EDplus11 | 0.050** (0.024) | 0.050** (0.023) | 0.050** (0.024) | -0.007 (0.024) | 0.050** (0.024) | 0.053** (0.024) |
| EDplus12 | 0.032 (0.023) | 0.032 (0.023) | 0.032 (0.025) | -0.023 (0.025) | 0.032 (0.022) | 0.032 (0.024) |
| EDplus13 | 0.016 (0.023) | 0.016 (0.022) | 0.016 (0.027) | -0.045 (0.027) | 0.016 (0.022) | 0.016 (0.022) |
| EDplus14 | 0.021 (0.022) | 0.021 (0.022) | 0.021 (0.027) | -0.046* (0.027) | 0.021 (0.021) | 0.021 (0.022) |
| EDplus15 | 0.017 (0.021) | 0.017 (0.020) | 0.017 (0.029) | -0.05* (0.029) | 0.356*** (0.010) | 0.356*** (0.010) |
| log (state GDP) | 0.451*** (0.068) | 0.451*** (0.066) | 0.451*** (0.026) | 0.451*** (0.026) | 0.451*** (0.066) | 0.356*** (0.010) |
| Itaipu royalties | 0.000* (0.000) | 0.000** (0.000) | 0.000*** (0.000) | 0.000 (0.000) | 0.000* (0.000) | 0.000* (0.000) |
| Precipitation | 0.000* (0.000) | 0.000* (0.000) | 0.000* (0.000) | -0.024*** (0.000) | 0.000* (0.000) | 0.000* (0.000) |
| Temperature | 0.002 (0.008) | 0.002 (0.008) | 0.002 (0.007) | -0.024*** (0.000) | 0.005 (0.008) | 0.005 (0.008) |
| Population | 0.000*** (0.000) | 0.000*** (0.000) | 0.000*** (0.000) | 0.000*** (0.000) | 0.000*** (0.000) | 0.000*** (0.000) |

Notes: ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.
Table S7: Sensitivity Analysis – regression results (dependent variable: Services Tax-ISS)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
<th>1) Relaxing the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>2) Without covariates (temperature, precipitation, royalties and state GDP)</th>
<th>3) Adding a covariate (population)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Model</td>
<td>A</td>
<td>B</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>0.052 (0.108)</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>0.109 (0.130)</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>EDminus5</td>
<td>0.052 (0.105)</td>
<td>0.052 (0.114)</td>
<td>0.069 (0.110)</td>
<td>-0.032 (0.120)</td>
</tr>
<tr>
<td>EDminus4</td>
<td>0.109 (0.126)</td>
<td>0.109 (0.110)</td>
<td>0.068 (0.120)</td>
<td>0.109 (0.132)</td>
</tr>
<tr>
<td>EDminus3</td>
<td>0.027 (0.128)</td>
<td>0.027 (0.112)</td>
<td>-0.044 (0.118)</td>
<td>0.027 (0.131)</td>
</tr>
<tr>
<td>EDminus2</td>
<td>0.069 (0.134)</td>
<td>0.069 (0.110)</td>
<td>-0.032 (0.120)</td>
<td>0.069 (0.137)</td>
</tr>
<tr>
<td>EDzero</td>
<td>0.590*** (0.096)</td>
<td>0.590*** (0.096)</td>
<td>0.590*** (0.138)</td>
<td>0.590*** (0.146)</td>
</tr>
<tr>
<td>EDplus1</td>
<td>1.561*** (0.395)</td>
<td>1.561*** (0.395)</td>
<td>1.561*** (0.138)</td>
<td>0.895*** (0.069)</td>
</tr>
<tr>
<td>EDplus2</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>-0.000* (0.001)</td>
<td>-0.001 (0.001)</td>
</tr>
<tr>
<td>EDplus3</td>
<td>0.000*** (0.000)</td>
<td>0.000*** (0.000)</td>
<td>0.000*** (0.000)</td>
<td>0.000*** (0.000)</td>
</tr>
<tr>
<td>EDplus4</td>
<td>0.000 (0.046)</td>
<td>0.013 (0.044)</td>
<td>0.013 (0.038)</td>
<td>-0.000 (0.012)</td>
</tr>
</tbody>
</table>

Notes: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.
### Table S8: Sensitivity Analysis – regression results (dependent variable: state transfers - ICMS)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Main Model</th>
<th>A</th>
<th>B</th>
<th>1) Relaxing the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>2) Without control covariates (temperature, precipitation, royalties and state GDP)</th>
<th>3) Adding a control covariate (population)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Specification alternatives</th>
<th>1)</th>
<th>2)</th>
<th>3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDminus5</td>
<td>0.061 (0.051)</td>
<td>0.061 (0.050)</td>
<td>0.061 (0.050)</td>
<td>0.052 (0.048)</td>
</tr>
<tr>
<td>EDminus4</td>
<td>0.033 (0.053)</td>
<td>0.033 (0.051)</td>
<td>0.033 (0.048)</td>
<td>0.014 (0.046)</td>
</tr>
<tr>
<td>EDminus3</td>
<td>0.051 (0.052)</td>
<td>0.051 (0.050)</td>
<td>0.051 (0.049)</td>
<td>0.031 (0.047)</td>
</tr>
<tr>
<td>EDminus2</td>
<td>0.064 (0.053)</td>
<td>0.064 (0.052)</td>
<td>0.064 (0.048)</td>
<td>0.027 (0.046)</td>
</tr>
<tr>
<td>EDzero</td>
<td>0.072 (0.062)</td>
<td>0.072 (0.060)</td>
<td>0.072* (0.042)</td>
<td>0.037 (0.040)</td>
</tr>
<tr>
<td>EDplus1</td>
<td>0.032 (0.054)</td>
<td>0.032 (0.052)</td>
<td>0.032 (0.042)</td>
<td>0.018 (0.039)</td>
</tr>
<tr>
<td>EDplus2</td>
<td>0.012 (0.060)</td>
<td>0.012 (0.058)</td>
<td>0.012 (0.042)</td>
<td>-0.024 (0.039)</td>
</tr>
<tr>
<td>EDplus3</td>
<td>0.030 (0.057)</td>
<td>0.030 (0.055)</td>
<td>0.030 (0.043)</td>
<td>-0.002 (0.040)</td>
</tr>
<tr>
<td>EDplus4</td>
<td>0.052 (0.059)</td>
<td>0.052 (0.058)</td>
<td>0.052 (0.043)</td>
<td>0.005 (0.040)</td>
</tr>
<tr>
<td>EDplus5</td>
<td>0.025 (0.057)</td>
<td>0.025 (0.055)</td>
<td>0.025 (0.045)</td>
<td>-0.002 (0.042)</td>
</tr>
<tr>
<td>EDplus6</td>
<td>0.080 (0.055)</td>
<td>0.080 (0.053)</td>
<td>0.080* (0.045)</td>
<td>0.051 (0.042)</td>
</tr>
<tr>
<td>EDplus7</td>
<td>0.111** (0.055)</td>
<td>0.111** (0.053)</td>
<td>0.111** (0.047)</td>
<td>0.070 (0.044)</td>
</tr>
<tr>
<td>EDplus8</td>
<td>0.203*** (0.061)</td>
<td>0.203*** (0.059)</td>
<td>0.203*** (0.049)</td>
<td>0.156*** (0.045)</td>
</tr>
<tr>
<td>EDplus9</td>
<td>0.156** (0.063)</td>
<td>0.156** (0.061)</td>
<td>0.156** (0.050)</td>
<td>0.099** (0.046)</td>
</tr>
<tr>
<td>EDplus10</td>
<td>0.116** (0.057)</td>
<td>0.116** (0.056)</td>
<td>0.116** (0.054)</td>
<td>0.060 (0.049)</td>
</tr>
<tr>
<td>EDplus11</td>
<td>0.115** (0.054)</td>
<td>0.115** (0.053)</td>
<td>0.115** (0.057)</td>
<td>0.052 (0.052)</td>
</tr>
<tr>
<td>EDplus12</td>
<td>0.060 (0.052)</td>
<td>0.060 (0.050)</td>
<td>0.060 (0.059)</td>
<td>0.003 (0.054)</td>
</tr>
<tr>
<td>EDplus13</td>
<td>0.030 (0.050)</td>
<td>0.030 (0.049)</td>
<td>0.030 (0.065)</td>
<td>-0.015 (0.059)</td>
</tr>
<tr>
<td>EDplus14</td>
<td>0.054 (0.044)</td>
<td>0.054 (0.043)</td>
<td>0.054 (0.065)</td>
<td>0.017 (0.058)</td>
</tr>
<tr>
<td>EDplus15</td>
<td>0.044 (0.044)</td>
<td>0.044 (0.043)</td>
<td>0.044 (0.070)</td>
<td>0.003 (0.063)</td>
</tr>
<tr>
<td>log (state GDP)</td>
<td>0.874*** (0.158)</td>
<td>0.874*** (0.153)</td>
<td>0.874*** (0.063)</td>
<td>0.821*** (0.021)</td>
</tr>
<tr>
<td>Itaipu royalties</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>-0.000*** (0.000)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000*** (0.000)</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.040** (0.020)</td>
<td>0.040** (0.019)</td>
<td>0.040** (0.017)</td>
<td>0.008* (0.004)</td>
</tr>
<tr>
<td>Population</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000*** (0.000)</td>
</tr>
</tbody>
</table>

**Notes:** ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.
<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Main Model</th>
<th>A</th>
<th>B</th>
<th>1) Relating the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>Specification alternatives</th>
<th>2) Without covariates (temperature, precipitation, royalties and state GDP)</th>
<th>3) Adding a covariate (population)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>EDminus5</td>
<td>-0.005 (0.019)</td>
<td>-0.005 (0.019)</td>
<td>-0.005 (0.024)</td>
<td>0.008 (0.028)</td>
<td>-0.005 (0.019)</td>
<td>-0.004 (0.019)</td>
<td></td>
</tr>
<tr>
<td>EDminus4</td>
<td>-0.021 (0.029)</td>
<td>-0.021 (0.028)</td>
<td>-0.021 (0.023)</td>
<td>0.004 (0.028)</td>
<td>-0.021 (0.029)</td>
<td>-0.021 (0.028)</td>
<td></td>
</tr>
<tr>
<td>EDminus3</td>
<td>-0.007 (0.018)</td>
<td>-0.007 (0.018)</td>
<td>-0.007 (0.023)</td>
<td>0.010 (0.028)</td>
<td>-0.007 (0.019)</td>
<td>-0.007 (0.018)</td>
<td></td>
</tr>
<tr>
<td>EDminus2</td>
<td>0.003 (0.018)</td>
<td>0.003 (0.018)</td>
<td>0.003 (0.023)</td>
<td>0.028 (0.027)</td>
<td>0.003 (0.018)</td>
<td>0.002 (0.018)</td>
<td></td>
</tr>
<tr>
<td>EDzero</td>
<td>0.009 (0.019)</td>
<td>0.009 (0.019)</td>
<td>0.009 (0.020)</td>
<td>0.032 (0.024)</td>
<td>0.009 (0.019)</td>
<td>0.010 (0.019)</td>
<td></td>
</tr>
<tr>
<td>EDplus1</td>
<td>0.009 (0.018)</td>
<td>0.009 (0.017)</td>
<td>0.009 (0.020)</td>
<td>0.020 (0.023)</td>
<td>0.009 (0.017)</td>
<td>0.010 (0.018)</td>
<td></td>
</tr>
<tr>
<td>EDplus2</td>
<td>-0.008 (0.017)</td>
<td>-0.008 (0.017)</td>
<td>-0.008 (0.020)</td>
<td>-0.002 (0.023)</td>
<td>-0.008 (0.016)</td>
<td>-0.008 (0.017)</td>
<td></td>
</tr>
<tr>
<td>EDplus3</td>
<td>-0.032 (0.048)</td>
<td>-0.032 (0.047)</td>
<td>-0.032 (0.020)</td>
<td>-0.026 (0.024)</td>
<td>-0.032 (0.048)</td>
<td>-0.033 (0.048)</td>
<td></td>
</tr>
<tr>
<td>EDplus4</td>
<td>-0.022 (0.021)</td>
<td>-0.022 (0.020)</td>
<td>-0.022 (0.020)</td>
<td>-0.014 (0.024)</td>
<td>-0.022 (0.020)</td>
<td>-0.023 (0.021)</td>
<td></td>
</tr>
<tr>
<td>EDplus5</td>
<td>-0.035 (0.027)</td>
<td>-0.035 (0.026)</td>
<td>-0.000735</td>
<td>-0.034 (0.025)</td>
<td>-0.035 (0.025)</td>
<td>-0.037 (0.026)</td>
<td></td>
</tr>
<tr>
<td>EDplus6</td>
<td>-0.030 (0.024)</td>
<td>-0.030 (0.023)</td>
<td>-0.030 (0.021)</td>
<td>-0.014 (0.025)</td>
<td>-0.030 (0.023)</td>
<td>-0.032 (0.024)</td>
<td></td>
</tr>
<tr>
<td>EDplus7</td>
<td>-0.001 (0.018)</td>
<td>-0.001 (0.018)</td>
<td>-0.001 (0.022)</td>
<td>0.022 (0.026)</td>
<td>-0.001 (0.017)</td>
<td>-0.002 (0.019)</td>
<td></td>
</tr>
<tr>
<td>EDplus8</td>
<td>-0.015 (0.021)</td>
<td>-0.015 (0.020)</td>
<td>-0.015 (0.023)</td>
<td>-0.001 (0.027)</td>
<td>-0.015 (0.019)</td>
<td>-0.016 (0.020)</td>
<td></td>
</tr>
<tr>
<td>EDplus9</td>
<td>-0.027 (0.019)</td>
<td>-0.027 (0.018)</td>
<td>-0.027 (0.023)</td>
<td>-0.014 (0.027)</td>
<td>-0.027 (0.020)</td>
<td>-0.027 (0.018)</td>
<td></td>
</tr>
<tr>
<td>EDplus10</td>
<td>-0.055*** (0.021)</td>
<td>-0.055*** (0.020)</td>
<td>-0.055** (0.025)</td>
<td>-0.038 (0.029)</td>
<td>-0.055*** (0.020)</td>
<td>-0.052** (0.020)</td>
<td></td>
</tr>
<tr>
<td>EDplus11</td>
<td>-0.052** (0.022)</td>
<td>-0.052** (0.021)</td>
<td>-0.052* (0.027)</td>
<td>-0.000 (0.031)</td>
<td>-0.052** (0.020)</td>
<td>-0.049** (0.022)</td>
<td></td>
</tr>
<tr>
<td>EDplus12</td>
<td>-0.062*** (0.023)</td>
<td>-0.062*** (0.022)</td>
<td>-0.062** (0.028)</td>
<td>-0.058* (0.032)</td>
<td>-0.062*** (0.019)</td>
<td>-0.062*** (0.023)</td>
<td></td>
</tr>
<tr>
<td>EDplus13</td>
<td>-0.057** (0.025)</td>
<td>-0.057** (0.025)</td>
<td>-0.057* (0.031)</td>
<td>-0.064* (0.035)</td>
<td>-0.057** (0.023)</td>
<td>-0.057** (0.025)</td>
<td></td>
</tr>
<tr>
<td>EDplus14</td>
<td>-0.117 (0.087)</td>
<td>-0.117 (0.085)</td>
<td>-0.117*** (0.030)</td>
<td>-0.141*** (0.035)</td>
<td>-0.117 (0.088)</td>
<td>-0.117 (0.088)</td>
<td></td>
</tr>
<tr>
<td>EDplus15</td>
<td>-0.040* (0.024)</td>
<td>-0.040* (0.024)</td>
<td>-0.040 (0.033)</td>
<td>-0.048 (0.038)</td>
<td>-0.040** (0.020)</td>
<td>-0.041* (0.024)</td>
<td></td>
</tr>
<tr>
<td>log (state GDP)</td>
<td>0.095 (0.078)</td>
<td>0.095 (0.075)</td>
<td>0.095*** (0.029)</td>
<td>0.004 (0.012)</td>
<td>0.079 (0.077)</td>
<td>0.079 (0.077)</td>
<td></td>
</tr>
<tr>
<td>Itaipu royalties</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td></td>
</tr>
<tr>
<td>Precipitation</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>0.002 (0.008)</td>
<td>0.002 (0.008)</td>
<td>0.002 (0.008)</td>
<td>-0.003 (0.003)</td>
<td>0.004 (0.008)</td>
<td>0.004 (0.008)</td>
<td></td>
</tr>
<tr>
<td>Population</td>
<td>0.000** (0.000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: *** Significant at the 1 percent level; ** Significant at the 5 percent level; * Significant at the 10 percent level.
7.4.3 Socioeconomic indicators

We applied a similar sensitivity analysis for the eight socioeconomic indicators: average income, life expectancy, educational level, access to piped water, access to public electricity, teenage pregnancy levels, and HIV cases. Annex B3 contains the detailed regression tables. Those estimates also indicate that failure to control for within-cluster error correlation lead to misleadingly small standard errors. Overall, the use of alternative specifications also suggests that the selected socioeconomic indicators are not affected by hydropower development after construction at the 5% level, supporting the results presented in Chapter 3.

7.5 Regressions checks

To provide additional information about the validity of our model assumptions, we developed a series of regression checks. First, we examined the residuals from our main regression to confirm that the basic ordinary least squares assumptions are valid. Second, we tested the strict exogeneity assumption by running alternative specifications using lagged covariates, and provided a lower bound estimate for the main model using an autoregressive model.

7.5.1 Residual diagnostics and clustered bootstrapping

Annex B2 contains six plots with standard regression diagnostics (distribution of the studentized residual, residuals vs. fitted values, Q-Q plot, scale location, cook’s distance, and a residuals vs. leverage) for each dependent economic variable evaluated in this study. The
analysis of the results confirms that the residual distributions have constant variance. However, the residuals vs. fitted values plot review the existence of outliers, and the distribution of the studentized residuals and Q-Q plots indicate that error distributions have a longer tail compared to the normal distribution. Although the cook’s distance and leverage vs. residuals plot indicate that those outliers are not influential, the normality assumption of the variance seems to be violated. This violation can affect the standard errors and, as a consequence, our inferences.

To investigate the effect of the lack of normal variance in regression standard errors, we performed a standard clustered bootstrapping procedure. Bootstrap methods generate a number of pseudo-samples from the original sample, for each pseudo-sample we calculate the statistic of interest, and use the distribution of this statistic across pseudo-samples to infer the distribution of the original sample statistic (Cameron, Gelbach & Miller 2008).

Table S12 and Table S13 compare the results from the clustered robust standard errors from the main model with clustered bootstrap standard errors for GDP and taxes, respectively. Table S12 shows that clustered bootstrap and the main model standard errors are qualitative similar. In contrast, Table S13 indicates that bootstrap standard errors are, in general, greater compared to the main model ones. This occurs because the deviation from the normal distribution is greater for taxes (Compare Q-Q plots in Annex B2). As a result, the substitution of the bootstrap standard errors for inference attenuates the statistical significance from our results. However, this analysis does not change our main conclusions, as most of the significant coefficients under the main model assumptions are still significant at 5% level using the average bootstrap standard errors.
Table S6: Comparison between the clustered robust standard errors from the main model and clustered bootstrap standard error statistics: Total GDP, Industry GDP, Services GDP and Agriculture GDP. Bootstrapping results: average and 95% confidence interval.

<table>
<thead>
<tr>
<th></th>
<th>Total GDP</th>
<th>Industry GDP</th>
<th>Services GDP</th>
<th>Agriculture GDP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Model</td>
<td>Bootstrapping</td>
<td>Main Model</td>
<td>Bootstrapping</td>
</tr>
<tr>
<td><strong>EDminus5</strong></td>
<td>0.045</td>
<td>0.043 (0.029-0.057)</td>
<td>0.125</td>
<td>0.109 (0.068-0.149)</td>
</tr>
<tr>
<td><strong>EDminus4</strong></td>
<td>0.028</td>
<td>0.034 (0.023-0.046)</td>
<td>0.121</td>
<td>0.103 (0.058-0.142)</td>
</tr>
<tr>
<td><strong>EDminus3</strong></td>
<td>0.031</td>
<td>0.031 (0.021-0.04)</td>
<td>0.177</td>
<td>0.154 (0.076-0.23)</td>
</tr>
<tr>
<td><strong>EDminus2</strong></td>
<td>0.033</td>
<td>0.03 (0.024-0.035)</td>
<td>0.141</td>
<td>0.105 (0.07-0.142)</td>
</tr>
<tr>
<td><strong>EDzero</strong></td>
<td>0.031</td>
<td>0.028 (0.022-0.036)</td>
<td>0.113</td>
<td>0.092 (0.068-0.123)</td>
</tr>
<tr>
<td><strong>EDplus1</strong></td>
<td>0.038</td>
<td>0.03 (0.024-0.037)</td>
<td>0.166</td>
<td>0.142 (0.103-0.179)</td>
</tr>
<tr>
<td><strong>EDplus2</strong></td>
<td>0.040</td>
<td>0.033 (0.027-0.041)</td>
<td>0.133</td>
<td>0.11 (0.081-0.14)</td>
</tr>
<tr>
<td><strong>EDplus3</strong></td>
<td>0.042</td>
<td>0.034 (0.028-0.042)</td>
<td>0.128</td>
<td>0.104 (0.078-0.13)</td>
</tr>
<tr>
<td><strong>EDplus4</strong></td>
<td>0.037</td>
<td>0.032 (0.026-0.037)</td>
<td>0.118</td>
<td>0.093 (0.075-0.116)</td>
</tr>
<tr>
<td><strong>EDplus5</strong></td>
<td>0.032</td>
<td>0.033 (0.026-0.039)</td>
<td>0.087</td>
<td>0.086 (0.071-0.099)</td>
</tr>
<tr>
<td><strong>EDplus6</strong></td>
<td>0.032</td>
<td>0.031 (0.026-0.037)</td>
<td>0.082</td>
<td>0.083 (0.069-0.098)</td>
</tr>
<tr>
<td><strong>EDplus7</strong></td>
<td>0.031</td>
<td>0.03 (0.024-0.036)</td>
<td>0.073</td>
<td>0.073 (0.061-0.085)</td>
</tr>
<tr>
<td><strong>EDplus8</strong></td>
<td>0.031</td>
<td>0.03 (0.022-0.038)</td>
<td>0.080</td>
<td>0.076 (0.06-0.094)</td>
</tr>
<tr>
<td><strong>EDplus9</strong></td>
<td>0.029</td>
<td>0.029 (0.021-0.036)</td>
<td>0.061</td>
<td>0.072 (0.059-0.089)</td>
</tr>
<tr>
<td><strong>EDplus10</strong></td>
<td>0.031</td>
<td>0.028 (0.023-0.035)</td>
<td>0.059</td>
<td>0.069 (0.054-0.09)</td>
</tr>
<tr>
<td><strong>EDplus11</strong></td>
<td>0.030</td>
<td>0.029 (0.022-0.036)</td>
<td>0.055</td>
<td>0.062 (0.049-0.078)</td>
</tr>
<tr>
<td><strong>EDplus12</strong></td>
<td>0.026</td>
<td>0.031 (0.023-0.039)</td>
<td>0.059</td>
<td>0.076 (0.059-0.096)</td>
</tr>
<tr>
<td><strong>EDplus13</strong></td>
<td>0.018</td>
<td>0.026 (0.019-0.035)</td>
<td>0.047</td>
<td>0.066 (0.053-0.08)</td>
</tr>
<tr>
<td><strong>EDplus14</strong></td>
<td>0.015</td>
<td>0.022 (0.016-0.03)</td>
<td>0.045</td>
<td>0.064 (0.045-0.085)</td>
</tr>
<tr>
<td><strong>EDplus15</strong></td>
<td>0.016</td>
<td>0.02 (0.013-0.028)</td>
<td>0.051</td>
<td>0.068 (0.041-0.097)</td>
</tr>
</tbody>
</table>
Table S7: Comparison between the clustered robust standard errors from the main model and clustered bootstrap standard error statistics: Public revenues, Services tax, State transfers and federal transfers. Bootstrapping results: average and 95% confidence interval.

<table>
<thead>
<tr>
<th></th>
<th>Public revenues</th>
<th>Services tax - ISS</th>
<th>State transfer - ICMS</th>
<th>Federal transfer - FPM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Model</td>
<td>Bootstrapping</td>
<td>Main Model</td>
<td>Bootstrapping</td>
</tr>
<tr>
<td>EDminus5</td>
<td>0.021</td>
<td>0.029 (0.023-0.035)</td>
<td>0.108</td>
<td>0.142 (0.114-0.172)</td>
</tr>
<tr>
<td>EDminus4</td>
<td>0.020</td>
<td>0.031 (0.026-0.037)</td>
<td>0.130</td>
<td>0.178 (0.144-0.21)</td>
</tr>
<tr>
<td>EDminus3</td>
<td>0.021</td>
<td>0.032 (0.026-0.037)</td>
<td>0.132</td>
<td>0.174 (0.134-0.215)</td>
</tr>
<tr>
<td>EDminus2</td>
<td>0.021</td>
<td>0.033 (0.027-0.039)</td>
<td>0.134</td>
<td>0.161 (0.131-0.194)</td>
</tr>
<tr>
<td>EDzero</td>
<td>0.023</td>
<td>0.039 (0.028-0.049)</td>
<td>0.144</td>
<td>0.188 (0.15-0.225)</td>
</tr>
<tr>
<td>EDplus1</td>
<td>0.026</td>
<td>0.044 (0.031-0.056)</td>
<td>0.161</td>
<td>0.248 (0.199-0.301)</td>
</tr>
<tr>
<td>EDplus2</td>
<td>0.028</td>
<td>0.052 (0.037-0.065)</td>
<td>0.168</td>
<td>0.282 (0.225-0.342)</td>
</tr>
<tr>
<td>EDplus3</td>
<td>0.028</td>
<td>0.048 (0.033-0.062)</td>
<td>0.158</td>
<td>0.252 (0.201-0.31)</td>
</tr>
<tr>
<td>EDplus4</td>
<td>0.028</td>
<td>0.046 (0.031-0.06)</td>
<td>0.145</td>
<td>0.218 (0.186-0.258)</td>
</tr>
<tr>
<td>EDplus5</td>
<td>0.027</td>
<td>0.044 (0.031-0.056)</td>
<td>0.145</td>
<td>0.21 (0.171-0.248)</td>
</tr>
<tr>
<td>EDplus6</td>
<td>0.027</td>
<td>0.037 (0.029-0.046)</td>
<td>0.144</td>
<td>0.21 (0.167-0.263)</td>
</tr>
<tr>
<td>EDplus7</td>
<td>0.024</td>
<td>0.034 (0.028-0.042)</td>
<td>0.148</td>
<td>0.241 (0.185-0.315)</td>
</tr>
<tr>
<td>EDplus8</td>
<td>0.025</td>
<td>0.035 (0.027-0.041)</td>
<td>0.151</td>
<td>0.231 (0.17-0.303)</td>
</tr>
<tr>
<td>EDplus9</td>
<td>0.026</td>
<td>0.038 (0.027-0.047)</td>
<td>0.148</td>
<td>0.283 (0.198-0.367)</td>
</tr>
<tr>
<td>EDplus10</td>
<td>0.026</td>
<td>0.032 (0.024-0.04)</td>
<td>0.142</td>
<td>0.242 (0.169-0.314)</td>
</tr>
<tr>
<td>EDplus11</td>
<td>0.024</td>
<td>0.028 (0.022-0.034)</td>
<td>0.141</td>
<td>0.23 (0.162-0.301)</td>
</tr>
<tr>
<td>EDplus12</td>
<td>0.024</td>
<td>0.03 (0.022-0.038)</td>
<td>0.133</td>
<td>0.206 (0.146-0.275)</td>
</tr>
<tr>
<td>EDplus13</td>
<td>0.023</td>
<td>0.031 (0.024-0.039)</td>
<td>0.118</td>
<td>0.146 (0.106-0.198)</td>
</tr>
<tr>
<td>EDplus14</td>
<td>0.022</td>
<td>0.031 (0.023-0.041)</td>
<td>0.130</td>
<td>0.162 (0.112-0.22)</td>
</tr>
<tr>
<td>EDplus15</td>
<td>0.021</td>
<td>0.03 (0.022-0.041)</td>
<td>0.145</td>
<td>0.188 (0.124-0.261)</td>
</tr>
</tbody>
</table>

7.5.2 Robustness checks

The basic unobserved effects model can be written, for a randomly drawn cross section observation $i$, as

$$y_{it} = x_{it} \beta + c_i + u_{it}$$ (1)

where, $x_{it}$ is a vector of observable variables that change across $t$ but not $i$, variables that change across $i$ but not $t$, and variables that change across $i$ and $t$. $c_i$ is the individual effect and $u_{it}$ the
idiosyncratic errors (Wooldridge 2004). For a linear panel data model, the strict exogeneity assumption can be formally stated by the following equation:

$$E(y_{it}|x_{it1}, x_{it2}, ... x_{itT}, c_i) = E(y_{it}|x_{it}, c_i) = x_{it}\beta + c_i$$  \hspace{1cm} (2)$$

For \( t=1,2,...,T \).

It means that, once \( x_{it} \) and \( c_i \) are controlled for, \( x_{is} \) has no partial effect on \( y_{is} \) for \( s't \) (Wooldridge 2004). Given equation (1), the idiosyncratic errors can be stated as

$$E(u_{it}|x_{it}, c_i) = 0$$  \hspace{1cm} (3)$$

This assumption denotes that explanatory variables in each time period are uncorrelated with the idiosyncratic errors in each time period (Wooldridge 2004):

$$E(x'_{is}u_{it}) = 0$$  \hspace{1cm} (4)$$

To check the strict exogeneity assumption, we employed a test proposed by Wooldridge (2004) using the following specification:

$$y_{it} = x_{it}\beta + \delta w_{it+1} + c_i + u_{it}$$  \hspace{1cm} (5)$$

where, \( w_{it+1} \) is a subset of \( x_{it+1} \) (that would exclude time dummies). Under the strict exogeneity, \( \delta \) should be equal to zero. The usual \( F \) statistic is valid here. Table S14 to Table S21 describes the results from this analysis in the last column (column 5). Further, we include a similar analysis.
but with lagged regressors (column 4) instead of the leads. The last row of the tables contains the
F-statistics and the correspondent p-values.

Moreover, we apply an autoregressive (AR) model to investigate a lower bound estimate
to be compared to our main model results. Angrist & Pischke (2008) shows that if the
unobserved effects model is correct and we mistakenly estimate an equation using lagged
outcomes like the equation 6 below, estimates of a positive treatment effect will tend to be too
small (Angrist & Pischke 2008). Therefore, the autoregressive model can be used as a lower
bound estimate and an additional check to our main model.

\[ y_{it} = x_{it}\beta + \delta y_{i,t-h} + c_i + u_{it} \] (6)

where \( y_{i,t-h} \) is a vector including lagged dependent variables for multiple periods.

Table S14 to Table S21 contain the regression estimates from five different
specifications. The first column reports the results from the main model. The second column is
similar to the main model but instead of 20 event-time dummies, we simplified the specification
by including only two event-time dummies that represent the averages in the construction
(EDzero to EDplus4) and operation (EDplus5 to EDplus15) stages. Based on this simpler model,
the third column presents the autoregressive (AR) specification (equation 6) with a lagged
dependent variable (Ylag), and fourth and fifth column present the strict exogeneity tests using
lags or leads of a subset of regressors (equation 5), respectively.

The lead regressors joint F-test (column 5) indicate that the strict exogeneity assumption
is violated for most of the indicators. The inconsistency from using fixed effects when the strict
exogeneity assumption fails is of order \( T^{-1} \). Thus, with large \( T \) the bias may be minimal.
(Wooldridge 2004). For our data, the estimated bias would be around 5% (T=20). Furthermore, our coefficients of interest (construction and operation) are not affected supporting the argument that our main results are robust.

As expected, the AR model construction and operation coefficients indicate a lower estimate in comparison to the main simpler event-time model. The AR values provide a lower bound for our main estimates and confirm the direction and order of magnitude of our main estimates.
Table S14: Comparison between the main model and other alternative specifications: a simpler event-time, an autoregressive, and lag/lead regressors model. Dependent variable: Total GDP

<table>
<thead>
<tr>
<th></th>
<th>Main Model (1)</th>
<th>Simple Model (2)</th>
<th>AR (3)</th>
<th>Lag Regressors (t-1) (4)</th>
<th>Lead Regressors (t+1) (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDminus5</td>
<td>0.025 (0.042)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDminus4</td>
<td>0.005 (0.025)</td>
<td></td>
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</tr>
<tr>
<td>EDminus3</td>
<td>-0.012 (0.032)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>EDminus2</td>
<td>-0.030 (0.034)</td>
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<td></td>
</tr>
<tr>
<td>EDzero</td>
<td>-0.000 (0.033)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDplus1</td>
<td>0.001 (0.040)</td>
<td></td>
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<tr>
<td>EDplus2</td>
<td>0.048 (0.043)</td>
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<tr>
<td>EDplus3</td>
<td>0.099*** (0.045)</td>
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<tr>
<td>EDplus4</td>
<td>0.092*** (0.040)</td>
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</tr>
<tr>
<td>EDplus5</td>
<td>0.094*** (0.032)</td>
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</tr>
<tr>
<td>EDplus6</td>
<td>0.066*** (0.034)</td>
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</tr>
<tr>
<td>EDplus7</td>
<td>0.062 (0.034)</td>
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<tr>
<td>EDplus8</td>
<td>0.066*** (0.033)</td>
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</tr>
<tr>
<td>EDplus9</td>
<td>0.061 (0.032)</td>
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</tr>
<tr>
<td>EDplus10</td>
<td>0.061 (0.033)</td>
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</tr>
<tr>
<td>EDplus11</td>
<td>0.059 (0.033)</td>
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</tr>
<tr>
<td>EDplus12</td>
<td>0.033 (0.030)</td>
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</tr>
<tr>
<td>EDplus13</td>
<td>0.016 (0.022)</td>
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</tr>
<tr>
<td>EDplus14</td>
<td>0.030 (0.018)</td>
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</tr>
<tr>
<td>EDplus15</td>
<td>0.047*** (0.018)</td>
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</tr>
<tr>
<td>Construction</td>
<td></td>
<td>0.047 (0.030)</td>
<td>0.017 (0.009)</td>
<td>0.040*** (0.013)</td>
<td>0.044*** (0.013)</td>
</tr>
<tr>
<td>Operation</td>
<td></td>
<td>0.052*** (0.022)</td>
<td>-0.006 (0.006)</td>
<td>0.048*** (0.011)</td>
<td>0.047*** (0.012)</td>
</tr>
<tr>
<td>Ylag</td>
<td></td>
<td></td>
<td>0.987*** (0.002)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>log (state GDP)</td>
<td>-121.633*** (25.338)</td>
<td></td>
<td>-129.437*** (26.654)</td>
<td>-7.255*** (1.814)</td>
<td>-98.748*** (23.564)</td>
</tr>
<tr>
<td>Itaipu royalties</td>
<td>0.006* (0.003)</td>
<td>0.007*** (0.003)</td>
<td>0.000*** (0.000)</td>
<td>0.008** (0.004)</td>
<td>0.008 (0.004)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
</tr>
<tr>
<td>Temperature</td>
<td>-0.011 (0.011)</td>
<td>-0.011 (0.012)</td>
<td>0.003*** (0.001)</td>
<td>0.020* (0.008)</td>
<td>-0.001 (0.010)</td>
</tr>
<tr>
<td>log (state GDP): t-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-38.538 (23.526)</td>
</tr>
<tr>
<td>Precipitation: t-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.000 (0.000)</td>
</tr>
<tr>
<td>Air Temperature: t-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.034*** (0.009)</td>
</tr>
<tr>
<td>log (state GDP): t+1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-25.555 (24.128)</td>
</tr>
<tr>
<td>Precipitation: t+1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.000 (0.000)</td>
</tr>
<tr>
<td>Air Temperature: t+1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.022*** (0.008)</td>
</tr>
</tbody>
</table>

Wald test for the subset of lag/lead covariates
(F-statistic/p-values) F = 7.51 / p = 5.2e-05 F = 3.97 / p = 0.007

Note: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.
Table S15: Comparison between the main model and other alternative specifications: a simpler event-time, an autoregressive, and lag/lead regressors model. Dependent variable: Industry GDP

<table>
<thead>
<tr>
<th></th>
<th>Main Model (1)</th>
<th>Simple Model (2)</th>
<th>AR (3)</th>
<th>Lag Regressors (t-1) (4)</th>
<th>Lead Regressors (t+1) (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDminus5</td>
<td>0.247* (0.136)</td>
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</tr>
<tr>
<td>EDminus4</td>
<td>0.221 (0.139)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>EDminus3</td>
<td>-0.023 (0.185)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDminus2</td>
<td>0.087 (0.154)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDzero</td>
<td>0.110 (0.122)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDplus1</td>
<td>0.064 (0.175)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDplus2</td>
<td>0.233 (0.148)</td>
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<td></td>
<td></td>
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<tr>
<td>EDplus3</td>
<td>0.325** (0.146)</td>
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<td></td>
</tr>
<tr>
<td>EDplus4</td>
<td>0.335** (0.132)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EDplus5</td>
<td>0.315*** (0.096)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EDplus6</td>
<td>0.275*** (0.093)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDplus7</td>
<td>0.265*** (0.084)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDplus8</td>
<td>0.320*** (0.098)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDplus9</td>
<td>0.219*** (0.073)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EDplus10</td>
<td>0.195*** (0.074)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EDplus11</td>
<td>0.164** (0.071)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDplus12</td>
<td>0.164** (0.071)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EDplus13</td>
<td>0.111** (0.055)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>EDplus14</td>
<td>0.082 (0.062)</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>EDplus15</td>
<td>0.115** (0.055)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td>0.148* (0.086)</td>
<td>0.053 (0.034)</td>
<td>0.114*** (0.031)</td>
<td>0.126*** (0.032)</td>
</tr>
<tr>
<td>Operation</td>
<td></td>
<td>0.177*** (0.051)</td>
<td>-0.002 (0.017)</td>
<td>0.154*** (0.024)</td>
<td>0.156*** (0.026)</td>
</tr>
<tr>
<td>Ylag</td>
<td></td>
<td></td>
<td>0.944*** (0.015)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>log (state GDP)</td>
<td>-293.048*** (74.784)</td>
<td>-316.459*** (77.630)</td>
<td>-41.039*** (12.540)</td>
<td>-246.480*** (58.150)</td>
<td>-271.969*** (60.342)</td>
</tr>
<tr>
<td>Itaipu royalties</td>
<td>0.003 (0.006)</td>
<td>0.004 (0.006)</td>
<td>-0.000 (0.001)</td>
<td>0.011** (0.005)</td>
<td>0.013** (0.006)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>0</td>
<td>0</td>
<td>0.000*** (0.000)</td>
<td>0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
</tr>
<tr>
<td>Temperature</td>
<td>-0.003256</td>
<td>-0.076 (0.046)</td>
<td>0.016*** (0.005)</td>
<td>0.022 (0.018)</td>
<td>0.022 (0.022)</td>
</tr>
<tr>
<td>log (state GDP): t-1</td>
<td></td>
<td></td>
<td></td>
<td>-0.048** (0.021)</td>
<td></td>
</tr>
<tr>
<td>Precipitation: t-1</td>
<td></td>
<td></td>
<td></td>
<td>-0.000 (0.000)</td>
<td></td>
</tr>
<tr>
<td>Air Temperature: t-1</td>
<td></td>
<td></td>
<td></td>
<td>-53.539 (59.876)</td>
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<tr>
<td>log (state GDP): t+1</td>
<td></td>
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<td></td>
<td>0.000 (0.000)</td>
<td></td>
</tr>
<tr>
<td>Precipitation: t+1</td>
<td></td>
<td></td>
<td></td>
<td>0.039** (0.018)</td>
<td></td>
</tr>
<tr>
<td>Air Temperature: t+1</td>
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</tr>
</tbody>
</table>

Wald test for the subset of lag/lead covariates

| (F-statistic/p-values) | F = 4.759/ p= 0.002 | F = 2.407/ p= 0.065 |

Note: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.
Table S16: Comparison between the main model and other alternative specifications: a simpler event-time, an autoregressive, and lag/lead regressors model. Dependent variable: Services GDP

<table>
<thead>
<tr>
<th></th>
<th>Main Model (1)</th>
<th>Simple Model (2)</th>
<th>AR (3)</th>
<th>Lag Regressors (t-1) (4)</th>
<th>Lead Regressors (t+1) (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDminus5</td>
<td>0.046 (0.033)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>EDminus4</td>
<td>0.018 (0.025)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDminus3</td>
<td>-0.007 (0.027)</td>
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<td></td>
</tr>
<tr>
<td>EDminus2</td>
<td>0.007 (0.021)</td>
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<tr>
<td>EDzero</td>
<td>0.035 (0.026)</td>
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</tr>
<tr>
<td>EDplus1</td>
<td>0.023 (0.028)</td>
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</tr>
<tr>
<td>EDplus2</td>
<td>0.033 (0.029)</td>
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<tr>
<td>EDplus3</td>
<td>0.069** (0.031)</td>
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<tr>
<td>EDplus4</td>
<td>0.058** (0.029)</td>
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</tr>
<tr>
<td>EDplus5</td>
<td>0.039 (0.025)</td>
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<tr>
<td>EDplus6</td>
<td>0.028 (0.026)</td>
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<tr>
<td>EDplus7</td>
<td>0.037 (0.030)</td>
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</tr>
<tr>
<td>EDplus8</td>
<td>0.026 (0.027)</td>
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<tr>
<td>EDplus9</td>
<td>0.031 (0.031)</td>
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<tr>
<td>EDplus10</td>
<td>0.038 (0.032)</td>
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</tr>
<tr>
<td>EDplus11</td>
<td>0.029 (0.029)</td>
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<tr>
<td>EDplus12</td>
<td>0.034 (0.025)</td>
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<tr>
<td>EDplus13</td>
<td>0.006 (0.023)</td>
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</tr>
<tr>
<td>EDplus14</td>
<td>0.006 (0.018)</td>
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<tr>
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<td>0.012 (0.014)</td>
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<tr>
<td>Construction</td>
<td></td>
<td>0.037* (0.022)</td>
<td>0.003 (0.004)</td>
<td>0.032*** (0.008)</td>
<td>0.032*** (0.008)</td>
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<td>Operation</td>
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<td>0.019** (0.008)</td>
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<tr>
<td>Ylag</td>
<td></td>
<td></td>
<td>0.995*** (0.001)</td>
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<tr>
<td>log (state GDP)</td>
<td>-73.878*** (16.264)</td>
<td>-76.872*** (16.766)</td>
<td>-3.727*** (0.797)</td>
<td>-69.087*** (15.425)</td>
<td>-68.235*** (16.620)</td>
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<td>Itaipu royalties</td>
<td>0.006* (0.003)</td>
<td>0.006** (0.003)</td>
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<td>-0.000*** (0.000)</td>
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<td>-0.000 (0.000)</td>
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<td>-0.001 (0.007)</td>
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<td>log (state GDP): t-1</td>
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<tr>
<td>Precipitation: t-1</td>
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<td>Air Temperature: t-1</td>
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<tr>
<td>log (state GDP): t+1</td>
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<tr>
<td>Precipitation: t+1</td>
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<td>Air Temperature: t+1</td>
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<td>Wald test for the subset of lag/lead covariates</td>
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<td>F = 4.781 / p = 0.002</td>
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Note: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.
Table S17: Comparison between the main model and other alternative specifications: a simpler event-time, an autoregressive, and lag/lead regressors model. Dependent variable: Agriculture GDP

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<th>Main Model (1)</th>
<th>Simple Model (2)</th>
<th>AR (3)</th>
<th>Lag Regressors (t) (4)</th>
<th>Lead Regressors (t+1) (5)</th>
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<td>EDminus3</td>
<td>-0.018 (0.054)</td>
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<tr>
<td>EDplus2</td>
<td>-0.039 (0.048)</td>
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<tr>
<td>EDplus3</td>
<td>-0.045 (0.054)</td>
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<td>EDplus6</td>
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<td>EDplus7</td>
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<td>EDplus9</td>
<td>-0.033 (0.051)</td>
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<td>EDplus10</td>
<td>-0.006 (0.048)</td>
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<td>EDplus11</td>
<td>0.037 (0.045)</td>
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<td>EDplus12</td>
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<td>EDplus13</td>
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<td>EDplus14</td>
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<td>EDplus15</td>
<td>0.047 (0.042)</td>
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<td>Construction</td>
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<td>-0.032 (0.020)</td>
<td>-0.021 (0.017)</td>
<td>-0.017 (0.018)</td>
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<td>-0.018 (0.012)</td>
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<td>-0.026 (0.016)</td>
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<td>-68.06 (25.872)</td>
<td>-13.12 (2.474)</td>
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<td>0.003 (0.002)</td>
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<td>0.003 (0.003)</td>
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<td>-0.000** (0.000)</td>
<td>0.000 (0.000)</td>
<td>-0.000** (0.000)</td>
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<tr>
<td>Temperature</td>
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<td>0.001 (0.001)</td>
<td>0.026** (0.012)</td>
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<td>log (state GDP): t-1</td>
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<td>Precipitation: t-1</td>
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<tr>
<td>Air Temperature: t-1</td>
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<td>-0.047*** (0.015)</td>
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<td>log (state GDP): t+1</td>
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<td>Precipitation: t+1</td>
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<td>-0.000*** (0.000)</td>
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<td>Air Temperature: t+1</td>
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<td>0.020* (0.012)</td>
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<tr>
<td>Wald test for the subset of lag/lead covariates</td>
<td>F = 6.043 / F = 6.829</td>
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<td>(F-statistic/p-values)</td>
<td>p= 0.0004</td>
<td>p= 0.0001</td>
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Note: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.
Table S18: Comparison between the main model and other alternative specifications: a simpler event-time, an autoregressive, and lag/lead regressors model. Dependent variable: Public revenues

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<th>Simple Model (2)</th>
<th>AR (3)</th>
<th>Lag Regressors (t-1) (4)</th>
<th>Lead Regressors (t+1) (5)</th>
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<td>EDminus4</td>
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<td>EDminus3</td>
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<td>0.052 (0.034)</td>
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<td>EDplus1</td>
<td>0.076* (0.039)</td>
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<tr>
<td>EDplus3</td>
<td>0.078* (0.044)</td>
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<tr>
<td>EDplus4</td>
<td>0.070 (0.043)</td>
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<tr>
<td>EDplus5</td>
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<tr>
<td>EDplus6</td>
<td>0.083** (0.035)</td>
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<tr>
<td>EDplus7</td>
<td>0.099*** (0.030)</td>
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<tr>
<td>EDplus8</td>
<td>0.115*** (0.032)</td>
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<td>EDplus9</td>
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<td>EDplus10</td>
<td>0.059** (0.025)</td>
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<tr>
<td>EDplus11</td>
<td>0.058** (0.023)</td>
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<tr>
<td>EDplus12</td>
<td>0.032 (0.024)</td>
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<tr>
<td>EDplus13</td>
<td>0.001 (0.023)</td>
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<td>EDplus14</td>
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<td>EDplus15</td>
<td>0.005 (0.028)</td>
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<tr>
<td>Construction</td>
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<tr>
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<td>0.005 (0.003)</td>
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<tr>
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<td>0.000* (0.000)</td>
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<td>Temperature</td>
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<td>log (state GDP): t-1</td>
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<td>0.000*** (0.000)</td>
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Wald test for the subset of lag/lead covariates (F-statistic/p-values): F = 9.703/ p= 2.2e-06 F = 11.281/ p= 2.2e-07

Note: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.
Table S19: Comparison between the main model and other alternative specifications: a simpler event-time, an autoregressive, and lag/lead regressors model. Dependent variable: Services tax - ISS

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<td>0.896*** (0.177)</td>
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<td>0.313*** (0.077)</td>
<td>0.913*** (0.060)</td>
<td>0.906*** (0.062)</td>
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<td>0.059 (0.051)</td>
<td>0.327*** (0.055)</td>
<td>0.338*** (0.061)</td>
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<td>Ylag</td>
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<td>log (state GDP)</td>
<td>411.180*** (88.229)</td>
<td>411.537*** (90.221)</td>
<td>-165.455*** (13.522)</td>
<td>-280.317** (131.101)</td>
<td>-271.488** (135.569)</td>
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<td>Itaipu royalties</td>
<td>0.010 (0.022)</td>
<td>0.006 (0.021)</td>
<td>-0.004*** (0.001)</td>
<td>0.006 (0.012)</td>
<td>0.005 (0.013)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>0.000*** (0.000)</td>
<td>0.000*** (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000*** (0.000)</td>
<td>0.000*** (0.000)</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.011 (0.072)</td>
<td>0.002 (0.072)</td>
<td>0.010 (0.007)</td>
<td>0.006 (0.041)</td>
<td>-0.067 (0.046)</td>
</tr>
<tr>
<td>log (state GDP): t-1</td>
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<td></td>
</tr>
<tr>
<td>Precipitation: t-1</td>
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<td></td>
<td></td>
<td></td>
<td>0.000*** (0.000)</td>
</tr>
<tr>
<td>Air Temperature: t-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.071 (0.044)</td>
</tr>
<tr>
<td>log (state GDP): t+1</td>
<td></td>
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<tr>
<td>Precipitation: t+1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.000*** (0.000)</td>
</tr>
<tr>
<td>Air Temperature: t+1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.000 (0.041)</td>
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Wald test for the subset of lag/lead covariates

(F-statistic/p-values)

F = 24.663 / F = 22.998/
P = 7.74e-16   P = 8.9e-15

Note: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.
Table S20: Comparison between the main model and other alternative specifications: a simpler event-time, an autoregressive, and lag/lead regressors model. Dependent variable: State transfers - ICMS

<table>
<thead>
<tr>
<th></th>
<th>Main Model (1)</th>
<th>Simple Model (2)</th>
<th>AR (3)</th>
<th>Lag Regressors (t-1) (4)</th>
<th>Lead Regressors (t+1) (5)</th>
</tr>
</thead>
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<tr>
<td>EDminus5</td>
<td>0.071 (0.080)</td>
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<tr>
<td>EDminus4</td>
<td>0.056 (0.085)</td>
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</tr>
<tr>
<td>EDminus3</td>
<td>0.074 (0.078)</td>
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</tr>
<tr>
<td>EDminus2</td>
<td>0.079 (0.082)</td>
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<td></td>
</tr>
<tr>
<td>EDzero</td>
<td>0.095 (0.100)</td>
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</tr>
<tr>
<td>EDplus1</td>
<td>0.055 (0.087)</td>
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</tr>
<tr>
<td>EDplus2</td>
<td>0.040 (0.099)</td>
<td></td>
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</tr>
<tr>
<td>EDplus3</td>
<td>0.059 (0.093)</td>
<td></td>
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</tr>
<tr>
<td>EDplus4</td>
<td>0.089 (0.099)</td>
<td></td>
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</tr>
<tr>
<td>EDplus5</td>
<td>0.054 (0.086)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>EDplus6</td>
<td>0.105 (0.086)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EDplus7</td>
<td>0.137* (0.078)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EDplus8</td>
<td>0.230*** (0.071)</td>
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</tr>
<tr>
<td>EDplus9</td>
<td>0.176** (0.073)</td>
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</tr>
<tr>
<td>EDplus10</td>
<td>0.125** (0.061)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>EDplus11</td>
<td>0.109* (0.061)</td>
<td></td>
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</tr>
<tr>
<td>EDplus12</td>
<td>0.041 (0.055)</td>
<td></td>
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</tr>
<tr>
<td>EDplus13</td>
<td>-0.012 (0.055)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDplus14</td>
<td>0.016 (0.047)</td>
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</tr>
<tr>
<td>EDplus15</td>
<td>0.019 (0.053)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Construction</td>
<td>0.045 (0.076)</td>
<td>0.034 (0.062)</td>
<td>0.019 (0.019)</td>
<td>0.010 (0.019)</td>
<td></td>
</tr>
<tr>
<td>Operation</td>
<td>0.087* (0.050)</td>
<td>0.070* (0.037)</td>
<td>0.075*** (0.019)</td>
<td>0.068*** (0.021)</td>
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</tr>
<tr>
<td>Ylag</td>
<td>0.705*** (0.010)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>log (state GDP)</td>
<td>-32.879 (59.995)</td>
<td>-31.217 (60.710)</td>
<td>-137.638*** (11.731)</td>
<td>-119.176** (50.885)</td>
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<td></td>
</tr>
<tr>
<td>Itaipu royalties</td>
<td>0.004 (0.004)</td>
<td>0.004 (0.003)</td>
<td>0.002 (0.001)</td>
<td>0.004** (0.002)</td>
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</tr>
<tr>
<td>Precipitation</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000* (0.000)</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>0.043 (0.029)</td>
<td>0.042 (0.029)</td>
<td>-0.000144</td>
<td>-0.011 (0.017)</td>
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</tr>
<tr>
<td>log (state GDP): t-1</td>
<td></td>
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<td></td>
<td>109.719** (45.483)</td>
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</tr>
<tr>
<td>Precipitation: t-1</td>
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<td></td>
<td></td>
<td>0.000** (0.000)</td>
<td></td>
</tr>
<tr>
<td>Air Temperature: t-1</td>
<td></td>
<td></td>
<td></td>
<td>0.070*** (0.020)</td>
<td></td>
</tr>
<tr>
<td>log (state GDP): t+1</td>
<td></td>
<td></td>
<td></td>
<td>99.999** (45.714)</td>
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</tr>
<tr>
<td>Precipitation: t+1</td>
<td></td>
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<td></td>
<td>0.000** (0.000)</td>
<td></td>
</tr>
<tr>
<td>Air Temperature: t+1</td>
<td></td>
<td></td>
<td></td>
<td>-0.034** (0.017)</td>
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</table>

Wald test for the subset of lag/lead covariates
(F-statistic/p-values) F = 12.339/ p= 4.8e-08 F = 15.701/ p= 3.6e-10

Note: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.
Table S21: Comparison between the main model and other alternative specifications: a simpler event-time, an autoregressive, and lag/lead regressors model. Dependent variable: Federal transfers - FPM

<table>
<thead>
<tr>
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<th>Main Model (1)</th>
<th>Simple Model (2)</th>
<th>AR (3)</th>
<th>Lag Regressors (t-1) (4)</th>
<th>Lead Regressors (t+1) (5)</th>
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<tbody>
<tr>
<td>EDminus5</td>
<td>-0.005 (0.016)</td>
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<td></td>
</tr>
<tr>
<td>EDminus4</td>
<td>-0.018 (0.029)</td>
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</tr>
<tr>
<td>EDminus3</td>
<td>-0.000 (0.020)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDminus2</td>
<td>0.011 (0.021)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDzero</td>
<td>0.020 (0.023)</td>
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<td></td>
</tr>
<tr>
<td>EDplus1</td>
<td>0.020 (0.020)</td>
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<tr>
<td>EDplus2</td>
<td>0.003 (0.018)</td>
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<td>EDplus3</td>
<td>-0.023 (0.048)</td>
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<tr>
<td>EDplus4</td>
<td>-0.012 (0.022)</td>
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<tr>
<td>EDplus5</td>
<td>-0.024 (0.023)</td>
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<tr>
<td>EDplus6</td>
<td>-0.020 (0.024)</td>
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<tr>
<td>EDplus7</td>
<td>0.009 (0.018)</td>
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<tr>
<td>EDplus8</td>
<td>-0.004 (0.022)</td>
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<tr>
<td>EDplus9</td>
<td>-0.014 (0.019)</td>
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<tr>
<td>EDplus10</td>
<td>-0.044** (0.021)</td>
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<tr>
<td>EDplus11</td>
<td>-0.041 (0.027)</td>
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<tr>
<td>EDplus12</td>
<td>-0.054* (0.031)</td>
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</tr>
<tr>
<td>EDplus13</td>
<td>-0.055* (0.031)</td>
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<tr>
<td>EDplus14</td>
<td>-0.116 (0.090)</td>
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<td></td>
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<tr>
<td>EDplus15</td>
<td>-0.041 (0.033)</td>
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</tr>
<tr>
<td>Construction</td>
<td>0.008 (0.018)</td>
<td>-0.019 (0.017)</td>
<td>-0.006 (0.036)</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.009 (0.011)</td>
<td></td>
<td>0.010 (0.011)</td>
</tr>
<tr>
<td>Operation</td>
<td></td>
<td></td>
<td>0.009 (0.011)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ylag</td>
<td></td>
<td></td>
<td>0.009 (0.011)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>log (state GDP)</td>
<td>-77.510*** (16.144)</td>
<td>-76.961*** (16.170)</td>
<td>-89.898*** (6.905)</td>
<td>-51.604*** (18.624)</td>
<td>-52.374*** (19.299)</td>
</tr>
<tr>
<td>Itaipu royalties</td>
<td>0.002 (0.002)</td>
<td>0.002 (0.002)</td>
<td>-0.003** (0.001)</td>
<td>0.001 (0.001)</td>
<td>0.001 (0.001)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.004 (0.009)</td>
<td>0.003 (0.008)</td>
<td>0.004 (0.003)</td>
<td>-0.008 (0.008)</td>
<td>0.001 (0.008)</td>
</tr>
<tr>
<td>log (state GDP): t-1</td>
<td></td>
<td></td>
<td>0.000*** (0.000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation: t-1</td>
<td></td>
<td></td>
<td>0.000*** (0.000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Temperature: t-1</td>
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<td></td>
<td>0.011 (0.010)</td>
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</tr>
<tr>
<td>log (state GDP): t+1</td>
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<td></td>
<td>-15.393 (15.359)</td>
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</tr>
<tr>
<td>Precipitation: t+1</td>
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<td>-0.000 (0.000)</td>
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</tr>
<tr>
<td>Air Temperature: t+1</td>
<td></td>
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<td></td>
<td>-0.003 (0.009)</td>
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</tbody>
</table>

Wald test for the subset of lag/lead covariates
(F-statistic/p-values)

F = 2.496 / p = 0.057
F = 1.265/ p= 0.264

Note: ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.
7.6 Complementary results and discussion

The number of people employed by a hydropower project varies according to power plant size and project phase. When construction starts, there is an immediate growth in local population and investments related to the construction of the hydropower plant. Each project creates direct jobs that are associated with dam construction, and indirect jobs, which are related to the additional demand for goods and services. When construction ends, part of the migrant workers leave, looking for new opportunities elsewhere. Figure S1 is an example (Teles Pires hydropower plant) of the variation in the number of people employed for each construction stage. It is interesting to note how the shape of ISS curve (Figure 3-3 from the Chapter 3) follows a pattern that is similar to the intensity of labor in the construction of hydropower plants. The ISS curve is characterized by a steep increase in the first year, achieving a peak during the second to fourth year, then followed by a steady decrease in the intensity. The fact that hydropower projects start operation in stages and the construction does not end abruptly drives this slow decrease in the ISS intensity. In the operation phase, the number of direct jobs varies from dozens to thousands of people, depending on the size of the power plant. Hydropower companies become a new industry in the area, providing new tax revenue. Usually, after construction the majority of jobs related to the dam disappear from the region.
7.6.1 Heterogeneity

In the Chapter 3, we present the average impact of hydropower development for the counties in our sample. Here, we explore how the different characteristics of projects (size and ownership) and counties (population size and level of human development) influenced our average estimates.

7.6.1.1 Larger (>500 MW) versus Smaller Dams (>30MW and <500 MW)

First, we evaluated how project size (based on installed capacity) affects our average estimates. Using our main model, we divided our sample into two groups: counties affected by
power plants with more than 500 MW (larger dams) and counties with hydropower plants between 30 and 500 MW of installed capacity (smaller dams). Figure S2 shows that the main difference between counties affected by larger and smaller dams is the negative Agriculture GDP associated with projects with more than 500 MW. As discussed in Chapter 3, this negative effect is probably associated with two main reasons: displacement of productive agricultural land by the reservoir flooding, and attraction of agricultural workers to new opportunities in the other economic sectors. Larger hydropower plants are often associated with larger reservoirs supporting the belief that flooding a large area significantly contribute to displace local agriculture output. As a result of this substantial negative effect on agricultural GDP, the overall performance of smaller hydropower plants is better when compared to the larger ones.

Hydropower plants with less than 500 MW also perform better in terms of tax revenues (Figure S3). Although the effect on the services tax is slightly superior for larger projects, smaller hydropower plants perform much better in terms of state transfers (ICMS). This result largely occurs because the ICMS is charged over the use of electricity in the point of consumption. Larger hydropower plants are usually connected to high voltage interstate transmission lines directly to the load centers and, therefore, the consumption of electricity does not happen in the region surrounding the dam. As a consequence, tax revenues increase on other regions. In contrast, smaller dams can be connected to regional grids, boosting local ICMS revenues.
Figure S2: Regression results for counties affected by hydropower plants of different sizes based on installed capacity: GDP
Figure S3: Regression results for counties affected by hydropower plants of different sizes based on installed capacity: tax revenues.
7.6.1.2 Utility versus Industry ownership

We also assess the importance of the ownership of hydropower plants on the economic outcomes. Industrial companies such as mining and aluminum manufacturing own some of the hydropower plants in our sample. Those hydropower plants are often associated with electric-intensive industrial projects from the same company. Thus, the industrial facilities consume most of the electricity generated by the associated hydropower plant, which we presume are close to the hydropower plants. Utility companies dedicated to the electricity business own the rest of the projects in our database. To explore the heterogeneity between those types of project owners, we divided the dataset into two groups: counties affected by power plant owned by utility companies or by industrial companies.

Figure S4 and Figure S5 present the comparison between those groups and show that the association between a hydropower project and an industrial facility results in better and more persistent economic outcomes. In terms of GDP, industrial-owned projects have a greater effect on the services sector, such that the total GDP is expressively more affected than the utility-owned projects. Industrial-owned projects also perform better in term of tax revenues, because of the greater local services tax and state transfers. The synergy between the hydropower plant construction and the industrial activity likely amplifies and extends the economic shock explaining the empirical difference observed in Figure S4 and Figure S5. However, we acknowledge that our analysis does not take into account the negative environmental and social impacts from this association.
Figure S4: Regression results for counties affected by hydropower plants with different ownership: GDP
Figure S5: Regression results for counties affected by hydropower plants with different ownership: tax revenues
7.6.1.3 Population Size

The population size of a county affected by a hydropower project is also expected to be a key factor driving heterogeneity in the economic outcomes. To explore the strength of this hypothesis, we divided the dataset into two groups: counties with less than 30,000 people in 1991 (“Small counties”) and counties with more than 30,000 people in 1991 (“Large counties”). We chose the value 30,000 because it is around the median population of the counties in our sample.

Figure S6 and S7 indicate that hydropower plants installed in large counties barely have an effect in either GDP or tax revenues indicators. On the other hand, the effect in the small counties is significant for all indicators demonstrating a clear distinction between small and large counties. This result is expected given that the shock produced by the hydropower plant should be greater in a small economy compared to the same shock in a larger economy.
Figure S6: Regression results for large vs. small counties affected by hydropower plants: GDP
Figure S7: Regression results for large vs. small counties affected by hydropower plants: tax revenues
7.6.1.4 Human development

The county human development levels should also be a central factor driving heterogeneity in the economic indicators. For example, a better-educated population should be more likely to be employed in new activities associated to the hydropower plant development, as well as to create new businesses to supply the new demand for goods and services. This characteristic should reduce the need for bringing temporary professionals or services to fulfill the additional demands, such that the benefit to the local economy is anticipated to be greater and longer. Similarly, more developed counties are expected to have a better infrastructure to alleviate the negative impacts and improve the positive ones. To investigate the importance of the human development level on the impacts of hydropower development on the local economy, we divided the counties into two groups: more developed counties (those with human development indexes greater than 0.4 in 1991) and less developed counties (those with human development indexes lower than 0.4 in 1991).

Figure S8 and Figure S9 indicate that more and less developed counties have qualitative similar results in terms of GDP and taxes. For some indicators, such as industry GDP and ISS, the average effect seems to be greater on less developed counties. However, the variance for the less developed counties is larger, such that it is difficult to characterize a clear difference between more and less developed counties.
Figure S8: Regression results for more vs. less developed counties affected by hydropower plants: GDP
Figure S9: Regression results for more vs. less developed counties affected by hydropower plants: tax revenues
7.6.2 The effect of the water resources financial compensation (WRFC) on counties affected by hydropower plants built before 1991

The water resources financial compensation (in Portuguese, *compensação financeira pela utilização dos recursos hídricos*) is a legal mechanism that requires dam owners to pay a fee for the water used to produce electricity. The fee is 6.75% of the monthly total energy produced by power plants multiplied by an energy tariff. The energy tariff is defined annually by the Brazilian electricity agency – ANEEL (Agencia Nacional de Energia Eletrica) – that is also responsible for collecting and distributing the WRFC fees. According to the law, 45% of the total WRFC resources are allocated to counties affected by the reservoirs, 45% to the states where the counties are located, and 10% to the federal government. In 2014, 183 hydropower reservoirs paid WRFC fees to ANEEL totaling 1.7 billion reais (~470 million USD given March 2016 foreign exchange rates). The idea behind the WRFC is to compensate places affected by hydropower reservoirs to mitigate social and environmental impacts, hoping to improve local welfare.

Here, we investigate the effects of the WRFC on the human development indicators alone by using a new group of counties as the treatment sample. This new group, called Group C, contains counties with a hydropower plant built before 1991 but that started receiving WRFC funds only in 1991, when the compensation policy was put into effect. The WRFC implementation represents a discontinuity for the treatment group and allows us to investigate the effect of the WRFC alone (excluding the construction effect). We applied the difference-in-difference specification (model 2 in Chapter 3) for the same socioeconomic indicators applied to groups A and B in Chapter 3.
Figure S10 reveals that the compensation policy positively affected the education indicator in the first decade of analysis and is significant at the 5% level. The average magnitude of the effect is approximately 1% greater (95% CI: 0% to 2%), but the coefficient is negative in the second period (-0.07%, 95% CI: 0% to -2%). Moreover, both the short- and long-run effects of the policy on income are negative and statistically significant, indicating a deleterious effect that increased over time. Additionally, the population density analysis suggests that the policy leads to an increase in population density by 8% (95% CI: 3% to 15%) in the long run.
Figure S10: Difference-in-differences regression results for the human development indicators and other outcomes of interest in WRFC treated counties (Group C). Bars represent the average \( \gamma_1 \) coefficients estimate from model 3 described in the methods section. Error bars represent the 95% confidence intervals defined as two times the standard errors (robust standard errors are clustered at the county level). Short term represents the first decade after hydropower development (1991-2000). Long term represents two decades after WRFC implementation (1991-2010).

The overall assessment from Figure S indicates that the WRFC policy had a short-term positive effect on the education indicator in the counties with hydropower plants built before
1991. However, the improved social conditions likely led to population migration to treated counties, increasing those counties’ populations. In the long term, population growth might have outweighed the benefits obtained from the increased WRFC funds. As a result, the short-term positive education outcome disappeared in the long run. Similarly, the decrease in average income in treated counties might be explained by an increase in the labor supply (and thus a decrease in job vacancies and wages) as a result of population growth. The only observed positive effect is a reduction of the teenage pregnancy rates, which can be explained by better educational conditions observed in the short-term.

Long-term population growth should also explain the negative effects on the percentage of households with access to electricity and piped water. It seems that local governments are not capable of keeping the same levels of service when facing a demographic pressure. As for HIV cases, the outcomes are not significantly affected by the WRFC policy. Therefore, there is evidence that the WRFC policy is not contributing to improve socioeconomic conditions in the long term. Indeed, the policy seems to be the underlying force behind negative outcomes.
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<td>MG</td>
<td>4203600</td>
<td>Campos Novos</td>
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<td>314500</td>
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<td>Capinzal</td>
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<tr>
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<td>MG</td>
<td>4204103</td>
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<td>SC</td>
<td>5211305</td>
<td>Itarumã</td>
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<td>314810</td>
<td>Patrocínio</td>
<td>MG</td>
<td>4204152</td>
<td>Celso Ramos</td>
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<td>5212501</td>
<td>Luziânia</td>
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<td>314920</td>
<td>Pedrinópolis</td>
<td>MG</td>
<td>4204178</td>
<td>Cerro Negro</td>
<td>SC</td>
<td>5213087</td>
<td>Minaçu</td>
<td>GO</td>
</tr>
<tr>
<td>314980</td>
<td>Perdizes</td>
<td>MG</td>
<td>4204202</td>
<td>Chapecó</td>
<td>SC</td>
<td>5214606</td>
<td>Niquelândia</td>
<td>GO</td>
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<tr>
<td>314990</td>
<td>Perdões</td>
<td>MG</td>
<td>4204301</td>
<td>Concórdia</td>
<td>SC</td>
<td>5215231</td>
<td>Novo Gama</td>
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<td>MG</td>
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<td>5217401</td>
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<td>MG</td>
<td>4206900</td>
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<td>315300</td>
<td>Resplendor</td>
<td>MG</td>
<td>4207601</td>
<td>Ipira</td>
<td>SC</td>
<td>5219456</td>
<td>Santa Rita do Novo Destino</td>
<td>GO</td>
</tr>
<tr>
<td>315500</td>
<td>Rio Doce</td>
<td>MG</td>
<td>4207684</td>
<td>Ipuaçu</td>
<td>SC</td>
<td>5219753</td>
<td>Santo Antônio do Descoberto</td>
<td>GO</td>
</tr>
<tr>
<td>315690</td>
<td>Sacramento</td>
<td>MG</td>
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<td>SC</td>
<td>5220504</td>
<td>Serranópolis</td>
<td>GO</td>
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<tr>
<td>315710</td>
<td>Salto da Divisa</td>
<td>MG</td>
<td>4209300</td>
<td>Lages</td>
<td>SC</td>
<td>5220603</td>
<td>Silvânia</td>
<td>GO</td>
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<td>315740</td>
<td>Santa Cruz do Escalvado</td>
<td>MG</td>
<td>4209904</td>
<td>Lontras</td>
<td>SC</td>
<td>5221601</td>
<td>Uruaçu</td>
<td>GO</td>
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<tr>
<td>315770</td>
<td>Santa Juliana</td>
<td>MG</td>
<td>4211876</td>
<td>Paial</td>
<td>SC</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
ANNEX B2 – Residual Diagnostics

Figure S11: Agricultural GDP regression residuals diagnostics (Model 1)
Figure S10: Industry GDP regression residuals diagnostics (Model 1)
Figure S13: Services GDP regression residuals diagnostics (Model 1)
Figures S14: Total GDP regression residuals diagnostics (Model 1)
Figure S15: Services Tax (ISS) regression residuals diagnostics (Model 1)
Figure S16: State Transfer (ICMS) regression residuals diagnostics (Model 1)
Figure S17: Federal Transfer (FPM) regression residuals diagnostics (Model 1)
Figure S18: Public revenue regression residuals diagnostics (Model 1)
ANNEX B3 – Sensitivity Analysis – Socioeconomic Indicators
Table S22: Sensitivity Analysis – regression results (dependent variable: average income; short term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Model</td>
<td>Without covariates (temperature, precipitation, royalties and state GDP)</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Ψ (Group A/ Short-term)

<table>
<thead>
<tr>
<th>T1 (Year 2000)</th>
<th>Group A</th>
<th>Precipitation</th>
<th>Air Temperature</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001 (0.009)</td>
<td>0.063***</td>
<td>-0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
</tr>
<tr>
<td>(0.001)</td>
<td>(0.004)</td>
<td>(0.026)</td>
<td>(0.008)</td>
<td>(0.002)</td>
</tr>
<tr>
<td>0.072***</td>
<td>0.072***</td>
<td>-0.018**</td>
<td>0.013 (0.009)</td>
<td>-0.000***</td>
</tr>
<tr>
<td>(0.027)</td>
<td>(0.026)</td>
<td>(0.008)</td>
<td>(0.006)</td>
<td>(0.000)</td>
</tr>
</tbody>
</table>

Notes: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.

Table S23: Sensitivity Analysis – regression results (dependent variable: average income; long term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Model</td>
<td>Without covariates (temperature, precipitation, royalties and state GDP)</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Ψ (Group A/ Long-term)

<table>
<thead>
<tr>
<th>T2 (Year 2010)</th>
<th>Group A</th>
<th>Precipitation</th>
<th>Air Temperature</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002 (0.015)</td>
<td>0.117***</td>
<td>0.000**</td>
<td>0.013 (0.009)</td>
<td>-0.000***</td>
</tr>
<tr>
<td>(0.007)</td>
<td>(0.007)</td>
<td>(0.000)</td>
<td>(0.000)</td>
<td>(0.000)</td>
</tr>
<tr>
<td>0.195***</td>
<td>0.195***</td>
<td>0.013***</td>
<td>0.013* (0.007)</td>
<td>-0.000***</td>
</tr>
<tr>
<td>(0.024)</td>
<td>(0.021)</td>
<td>(0.000)</td>
<td>(0.004)</td>
<td>(0.000)</td>
</tr>
</tbody>
</table>

Notes: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.
### Table S24: Sensitivity Analysis – regression results (dependent variable: average income; short term; Group B)

<table>
<thead>
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<th>Clustering Alternatives</th>
<th>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Model</td>
<td>A</td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ψ (Group B/ Short-term)</th>
<th>0.001 (0.006)</th>
<th>0.001 (0.006)</th>
<th>0.001 (0.004)</th>
<th>0.003 (0.006)</th>
<th>0.001 (0.006)</th>
<th>0.001 (0.006)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.062***</td>
<td>0.062***</td>
<td>0.062***</td>
<td>0.062***</td>
<td>0.068*** (0.001)</td>
<td>0.063***</td>
</tr>
<tr>
<td>T2 (Year 2010)</td>
<td>(0.003)</td>
<td>(0.005)</td>
<td>(0.004)</td>
<td>(0.001)</td>
<td>(0.003)</td>
<td></td>
</tr>
<tr>
<td>Group B</td>
<td>0.205***</td>
<td>0.205***</td>
<td>0.205***</td>
<td>0.181***</td>
<td>0.205***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.024)</td>
<td>(0.029)</td>
<td>(0.033)</td>
<td>(0.008)</td>
<td>(0.024)</td>
<td></td>
</tr>
<tr>
<td>Precipitation</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Temperature</td>
<td>0.008** (0.004)</td>
<td>0.008* (0.005)</td>
<td>0.008** (0.003)</td>
<td>(0.001)</td>
<td>0.007** (0.004)</td>
<td></td>
</tr>
<tr>
<td>Population</td>
<td>-0.000 (0.000)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Notes: ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.

### Table 25: Sensitivity Analysis – regression results (dependent variable: education; short term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>Specification alternatives</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Main Model</td>
<td>A</td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ψ (Group A/ Short-term)</th>
<th>0.017 (0.015)</th>
<th>0.017 (0.012)</th>
<th>0.017** (0.008)</th>
<th>0.023 (0.020)</th>
<th>0.026 (0.022)</th>
<th>0.017 (0.015)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.200***</td>
<td>0.200***</td>
<td>0.200***</td>
<td>0.203***</td>
<td>0.195*** (0.003)</td>
<td>0.201***</td>
</tr>
<tr>
<td>T1 (Year 2000)</td>
<td>(0.004)</td>
<td>(0.007)</td>
<td>(0.004)</td>
<td>(0.000)</td>
<td>(0.003)</td>
<td></td>
</tr>
<tr>
<td>Group A</td>
<td>-0.032 (0.073)</td>
<td>-0.032 (0.041)</td>
<td>-0.032 (0.039)</td>
<td>(0.011)</td>
<td>0.124*** (0.011)</td>
<td>-0.026 (0.073)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>(0.000)</td>
<td>-0.000 (0.000)</td>
<td></td>
</tr>
<tr>
<td>Air Temperature</td>
<td>-0.051** (0.024)</td>
<td>(0.014)</td>
<td>(0.007)</td>
<td>(0.002)</td>
<td>-0.051** (0.024)</td>
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</tr>
<tr>
<td>Population</td>
<td>-0.000 (0.000)</td>
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<td></td>
<td></td>
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Notes: ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.
### Table S26: Sensitivity Analysis – regression results (dependent variable: education; long term; Group A)

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<td>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</td>
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<td>Main Model</td>
<td>A</td>
</tr>
<tr>
<td>Standard errors</td>
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<tr>
<td>clustered by county:</td>
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</tr>
<tr>
<td>Standard errors</td>
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</tr>
<tr>
<td>clustered by hydropower plant:</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year</td>
<td></td>
</tr>
<tr>
<td>Fixed Effects</td>
<td>Yes</td>
</tr>
<tr>
<td>Ψ (Group A/ Long-term)</td>
<td>0.007 (0.015)</td>
</tr>
<tr>
<td></td>
<td>0.386***</td>
</tr>
<tr>
<td>T2 (Year 2010)</td>
<td>(0.010)</td>
</tr>
<tr>
<td>Group A</td>
<td>0.132***</td>
</tr>
<tr>
<td></td>
<td>(0.038)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>0.000 (0.000)</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>-0.005 (0.012)</td>
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<tr>
<td>Population</td>
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**Notes:** ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.

### Table 27: Sensitivity Analysis – regression results (dependent variable: education; short term; Group B)

<table>
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</tr>
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<td>Main Model</td>
<td>A</td>
</tr>
<tr>
<td>Standard errors</td>
<td></td>
</tr>
<tr>
<td>clustered by county:</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors</td>
<td></td>
</tr>
<tr>
<td>clustered by hydropower plant:</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year</td>
<td></td>
</tr>
<tr>
<td>Fixed Effects</td>
<td>Yes</td>
</tr>
<tr>
<td>Ψ (Group B/ Short-term)</td>
<td>0.010 (0.012)</td>
</tr>
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<td></td>
<td>0.183***</td>
</tr>
<tr>
<td>T2 (Year 2010)</td>
<td>(0.005)</td>
</tr>
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<td>Group B</td>
<td>0.192***</td>
</tr>
<tr>
<td></td>
<td>(0.048)</td>
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<tr>
<td>Precipitation</td>
<td>-0.000***</td>
</tr>
<tr>
<td></td>
<td>(0.000)</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>0.015** (0.007)</td>
</tr>
<tr>
<td>Population</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:** ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.
Table S28: Sensitivity Analysis – regression results (dependent variable: longevity; short term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Model</td>
<td>Without covariates (temperature, precipitation, royalties and state GDP)</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

| Ψ (Group A/ Short-term) | 0.007 (0.006) | 0.007 (0.005) | 0.007* (0.004) | 0.004 (0.007) | 0.003 (0.009) | 0.007 (0.006) |
| T1 (Year 2000) | 0.070*** (0.001) | 0.070*** (0.003) | 0.070*** (0.002) | 0.069*** (0.000) | 0.071*** (0.001) | 0.070*** (0.001) |
| Group A | 0.116*** (0.019) | 0.116*** (0.015) | 0.116*** (0.018) | 0.091*** (0.004) | 0.051*** (0.005) | 0.116*** (0.018) |
| Precipitation | -0.000 (0.000) | -0.000 (0.000) | -0.000 (0.000) | 0.000*** (0.000) | -0.000 (0.000) | -0.000 (0.000) |
| Air Temperature | 0.020*** (0.006) | 0.020*** (0.005) | 0.020*** (0.003) | 0.015*** (0.001) | 0.020*** (0.006) | |
| Population | 0.000 (0.000) | 0.000 (0.000) | 0.000 (0.000) | 0.000 (0.000) | 0.000 (0.000) | 0.000 (0.000) |

Notes: *** Significant at the 1 percent level;** Significant at the 5 percent level;* Significant at the 10 percent level.

Table S29: Sensitivity Analysis – regression results (dependent variable: longevity; long term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Model</td>
<td>Without covariates (temperature, precipitation, royalties and state GDP)</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

| Ψ (Group A/ Long-term) | 0.003 (0.018) | 0.003 (0.010) | 0.003 (0.006) | -0.005 (0.015) | 0.001 (0.016) | 0.003 (0.018) |
| T2 (Year 2010) | 0.133*** (0.009) | 0.133*** (0.006) | 0.133*** (0.004) | 0.145*** (0.001) | 0.141*** (0.001) | 0.133*** (0.009) |
| Group A | 0.135*** (0.031) | 0.135*** (0.018) | 0.135*** (0.025) | 0.114*** (0.007) | 0.079*** (0.008) | 0.138*** (0.031) |
| Precipitation | -0.000*** (0.000) | -0.000*** (0.000) | -0.000*** (0.000) | -0.000*** (0.000) | -0.000*** (0.000) | -0.000*** (0.000) |
| Air Temperature | 0.015 (0.011) | 0.015** (0.007) | 0.015** (0.004) | 0.007*** (0.002) | 0.015 (0.011) | |
| Population | -0.000 (0.000) | -0.000 (0.000) | -0.000 (0.000) | -0.000 (0.000) | -0.000 (0.000) | -0.000 (0.000) |

Notes: *** Significant at the 1 percent level;** Significant at the 5 percent level;* Significant at the 10 percent level.
### Table S30: Sensitivity Analysis – regression results (dependent variable: longevity; short term; Group B)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specifying alternatives</th>
<th>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>Without covariates (temperature, precipitation, royalties and state GDP)</th>
<th>Adding a covariate (population)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ψ (Group B/ Short-term)</th>
<th>0.006 (0.008)</th>
<th>-0.006 (0.007)</th>
<th>-0.006 (0.004)</th>
<th>-0.009 (0.008)</th>
<th>-0.004 (0.009)</th>
<th>-0.006 (0.008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2 (Year 2010)</td>
<td>0.073*** (0.004)</td>
<td>0.073*** (0.005)</td>
<td>0.073*** (0.004)</td>
<td>0.074*** (0.000)</td>
<td>0.071*** (0.002)</td>
<td>0.073*** (0.004)</td>
</tr>
<tr>
<td>Group B</td>
<td>0.085** (0.034)</td>
<td>0.085** (0.034)</td>
<td>0.085** (0.036)</td>
<td>(0.008)</td>
<td>0.095*** (0.004)</td>
<td>0.084** (0.034)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>0 (0.000)</td>
<td>0 (0.000)</td>
<td>-0.002 (0.005)</td>
<td>0.001</td>
<td>-0.002 (0.005)</td>
<td>-0.002 (0.005)</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>-0.002 (0.005)</td>
<td>-0.002 (0.005)</td>
<td>-0.002 (0.004)</td>
<td>-0.002 (0.005)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Population</td>
<td>-0.002 (0.005)</td>
<td>-0.002 (0.005)</td>
<td>-0.002 (0.004)</td>
<td>-0.002 (0.005)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:** ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.

### Table S31: Sensitivity Analysis – regression results (dependent variable: population density; short term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specifying alternatives</th>
<th>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>Without covariates (temperature, precipitation, royalties and state GDP)</th>
<th>Adding a covariate (population)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ψ (Group A/ Short-term)</th>
<th>0.023 (0.053)</th>
<th>0.023 (0.047)</th>
<th>0.023 (0.034)</th>
<th>-0.017 (0.052)</th>
<th>0.012 (0.054)</th>
<th>0.033 (0.050)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 (Year 2000)</td>
<td>0.035*** (0.010)</td>
<td>0.035 (0.041)</td>
<td>0.035* (0.019)</td>
<td>0.076*** (0.002)</td>
<td>0.035*** (0.002)</td>
<td>0.016 (0.012)</td>
</tr>
<tr>
<td>Group A</td>
<td>1.138*** (0.160)</td>
<td>1.138*** (0.146)</td>
<td>1.138*** (0.169)</td>
<td>1.175*** (0.028)</td>
<td>0.962*** (0.027)</td>
<td>0.965*** (0.132)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
<td>-0.000*** (0.000)</td>
<td>-0.000 (0.000)</td>
<td>-0.000 (0.000)</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>0.051 (0.056)</td>
<td>0.051 (0.060)</td>
<td>0.051 (0.032)</td>
<td>0.053*** (0.003)</td>
<td>0.046 (0.051)</td>
<td>0.000*** (0.000)</td>
</tr>
<tr>
<td>Population</td>
<td>0.000*** (0.000)</td>
<td>0.000*** (0.000)</td>
<td>0.000*** (0.000)</td>
<td>0.000*** (0.000)</td>
<td>0.000*** (0.000)</td>
<td>0.000*** (0.000)</td>
</tr>
</tbody>
</table>

**Notes:** ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.
Table S32: Sensitivity Analysis – regression results (dependent variable: population density; long term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</td>
</tr>
<tr>
<td><strong>Main Model</strong></td>
<td><strong>A</strong></td>
</tr>
</tbody>
</table>

| **Standard errors clustered by county:** | **Yes** | **Yes** | **No** | **Yes** | **Yes** | **Yes** |
| **Standard errors clustered by hydropower plant:** | **Yes** | **No** | **No** | **Yes** | **Yes** | **Yes** |
| **County and Year Fixed Effects** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** |

| **Ψ (Group A/ Long-term)** | **0.028 (0.078)** | **0.028 (0.069)** | **0.028 (0.049)** | **-0.015 (0.087)** | **0.042 (0.084)** | **0.048 (0.074)** |
| **T2 (Year 2010)** | **0.127*** (0.043)** | **0.127** (0.063) | **0.127*** (0.035) | **0.121*** (0.008) | **0.077*** (0.003) | **0.091** (0.041) |
| **Group A** | **0.988*** (0.143)** | **0.988*** (0.129) | **0.988*** (0.216) | **1.127*** (0.044) | **1.009*** (0.042) | **0.850*** (0.140) |
| **Precipitation** | **-0.000*** (0.000)** | **-0.000*** (0.000) | **-0.000*** (0.000) | **-0.000 (0.000)** | **-0.000*** (0.000) | **-0.000*** (0.000) |
| **Air Temperature** | **-0.036 (0.055)** | **-0.036 (0.048)** | **-0.036 (0.030)** | **0.025*** (0.005) | **-0.035 (0.052)** | **0.000*** (0.000) |
| **Population** | **0.000*** (0.000)** | **0.000*** (0.000)** | **0.000*** (0.000)** | **0.000*** (0.000)** | **0.000*** (0.000)** | **0.000*** (0.000)** |

**Notes:** ***Significant at the 1 percent level;**Significant at the 5 percent level;* Significant at the 10 percent level.

Table S33: Sensitivity Analysis – regression results (dependent variable: population density; short term; Group B)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</td>
</tr>
<tr>
<td><strong>Main Model</strong></td>
<td><strong>A</strong></td>
</tr>
</tbody>
</table>

| **Standard errors clustered by county:** | **Yes** | **Yes** | **No** | **Yes** | **Yes** | **Yes** |
| **Standard errors clustered by hydropower plant:** | **Yes** | **No** | **No** | **Yes** | **Yes** | **Yes** |
| **County and Year Fixed Effects** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** | **Yes** |

| **Ψ (Group B/ Short-term)** | **0.008 (0.028)** | **0.008 (0.027)** | **0.008 (0.019)** | **0.005 (0.031)** | **0.014 (0.030)** | **0.000 (0.023)** |
| **T2 (Year 2010)** | **0.057*** (0.023)** | **0.057*** (0.024) | **0.057*** (0.016) | **0.062*** (0.002) | **0.045*** (0.005) | **0.039** (0.020) |
| **Group B** | **0.018 (0.195)** | **0.018 (0.167)** | **0.018 (0.151)** | **0.025 (0.002)** | **0.114*** (0.015) | **0.027 (0.168)** |
| **Precipitation** | **-0.000*** (0.000)** | **0** | **-0.000*** (0.000) | **0.000*** (0.000) | **-0.000*** (0.000) | **-0.000*** (0.000) |
| **Air Temperature** | **-0.017 (0.031)** | **-0.017 (0.026)** | **-0.017 (0.016)** | **-0.008** (0.004) | **-0.011 (0.026)** | **0.000*** (0.000) |
| **Population** | **0.000*** (0.000)** | **0.000*** (0.000)** | **0.000*** (0.000)** | **0.000*** (0.000)** | **0.000*** (0.000)** | **0.000*** (0.000)** |

**Notes:** ***Significant at the 1 percent level;**Significant at the 5 percent level;* Significant at the 10 percent level.
Table S34: Sensitivity Analysis – regression results (dependent variable: access to piped water; short term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</td>
</tr>
<tr>
<td><strong>Main Model</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>A</strong></td>
<td>-1.940 (3.814)</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>-1.940 (3.142)</td>
</tr>
<tr>
<td><strong>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</strong></td>
<td>16.111*** (1.530)</td>
</tr>
<tr>
<td><strong>Without covariates</strong></td>
<td>1.396 (4.054)</td>
</tr>
<tr>
<td><strong>Adding a covariate</strong></td>
<td>-2.889 (4.022)</td>
</tr>
</tbody>
</table>
| **Notes**: ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.

Table S35: Sensitivity Analysis – regression results (dependent variable: access to piped water; short term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</td>
</tr>
<tr>
<td><strong>Main Model</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>A</strong></td>
<td>-5.855 (7.771)</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>-5.855 (4.263)</td>
</tr>
<tr>
<td><strong>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</strong></td>
<td>-18.531075</td>
</tr>
<tr>
<td><strong>Without covariates</strong></td>
<td>-18.531075</td>
</tr>
<tr>
<td><strong>Adding a covariate</strong></td>
<td>-5.768 (6.660)</td>
</tr>
<tr>
<td><strong>Population</strong></td>
<td>-6.702 (7.343)</td>
</tr>
</tbody>
</table>
| **Notes**: ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.
### Table S36: Sensitivity Analysis – regression results (dependent variable: access to piped water; short term; Group B)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main Model</strong></td>
<td></td>
<td><strong>Without covariates</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Adding a covariate</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>(temperature, precipitation, royalties and state GDP)</strong></td>
</tr>
<tr>
<td><strong>Clustering Alternatives</strong></td>
<td><strong>Specification alternatives</strong></td>
<td><strong>Adding a covariate</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>(population)</strong></td>
</tr>
<tr>
<td><strong>Main Model</strong></td>
<td></td>
<td><strong>Without covariates</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Adding a covariate</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>(temperature, precipitation, royalties and state GDP)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>(population)</strong></td>
</tr>
<tr>
<td><strong>Standard errors clustered by county:</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Standard errors clustered by hydropower plant:</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>County and Year Fixed Effects</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

| Ψ (Group B/ Short-term) | -0.232 (4.354) | -0.232 (3.221) | -0.232 (2.263) | 0.023 (4.051) | 1.661 (4.788) | -0.238 (4.390) |
| T2 (Year 2010)          | 11.175*** (2.083) | 11.175*** (2.520) | 11.175*** (1.959) | 12.148*** (0.181) | 11.456*** (1.471) | 11.162*** (2.242) |
| Group B                 | 45.384** (17.567) | 45.384*** (15.209) | 45.384*** (18.196) | 34.370*** (5.191) | 39.905*** (2.394) | 45.391** (17.634) |
| Precipitation           | -0.030*** (0.005) | -0.030*** (0.006) | -0.030*** (0.005) | -0.031*** (0.001) | -0.030*** (0.006) | -0.030*** (0.006) |
| Air Temperature         | 0.362 (2.656) | 0.362 (2.312) | 0.362 (1.873) | -1.360** (0.691) | 0.366 (2.679) |
| Population              | 0.000 (0.000) |

**Notes:** ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.

### Table S37: Sensitivity Analysis – regression results (dependent variable: access to electricity; short term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main Model</strong></td>
<td></td>
<td><strong>Without covariates</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Adding a covariate</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>(temperature, precipitation, royalties and state GDP)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>(population)</strong></td>
</tr>
<tr>
<td><strong>Clustering Alternatives</strong></td>
<td><strong>Specification alternatives</strong></td>
<td><strong>Adding a covariate</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>(temperature, precipitation, royalties and state GDP)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>(population)</strong></td>
</tr>
<tr>
<td><strong>Main Model</strong></td>
<td></td>
<td><strong>Without covariates</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Adding a covariate</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>(temperature, precipitation, royalties and state GDP)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>(population)</strong></td>
</tr>
<tr>
<td><strong>Standard errors clustered by county:</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Standard errors clustered by hydropower plant:</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>County and Year Fixed Effects</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

| Ψ (Group A/ Short-term) | -3.067 (2.583) | -3.067 (2.244) | -3.067 (1.887) | -0.256 (3.859) | -4.781 (3.581) | -3.360 (2.548) |
| T1 (Year 2000)          | 15.368*** (0.441) | 15.368*** (1.618) | 15.368*** (1.049) | 10.439*** (0.255) | 15.296*** (0.379) | 15.864*** (0.478) |
| Group A                 | 80.625*** (7.835) | 80.625*** (8.087) | 80.625*** (9.360) | 64.123*** (1.995) | 49.347*** (1.790) | 85.334*** (6.846) |
| Precipitation           | -0.006 (0.005) | -0.006 (0.008) | -0.006 (0.005) | 0.016*** (0.001) | -0.005 (0.005) |
| Air Temperature         | 9.127*** (2.255) | 9.127*** (2.222) | 9.127*** (1.819) | 6.658*** (0.122) | 9.313*** (2.123) |
| Population              | -0.000*** (0.000) |

**Notes:** ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.
### Table S38: Sensitivity Analysis – regression results (dependent variable: access to electricity; long term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relaxes the restriction of using only counties with unexplored hydropower potential as controls</td>
</tr>
<tr>
<td><strong>Main Model</strong> A B</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
</tr>
</tbody>
</table>

#### Notes:
- ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.

### Table S39: Sensitivity Analysis – regression results (dependent variable: access to electricity; short term; Group B)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relaxes the restriction of using only counties with unexplored hydropower potential as controls</td>
</tr>
<tr>
<td><strong>Main Model</strong> A B</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
</tr>
</tbody>
</table>

#### Notes:
- ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.
Table S40: Sensitivity Analysis – regression results (dependent variable: teenage pregnancy; short term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
<th>Specification alternatives</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</td>
<td>Without covariates (temperature, precipitation, royalties and state GDP)</td>
<td>Adding a covariate (population)</td>
</tr>
<tr>
<td><strong>Main Model</strong></td>
<td><strong>A</strong></td>
<td><strong>B</strong></td>
<td><strong>A</strong></td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Ψ (Group A/ Short-term)

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.433 (0.615)</td>
<td>-0.433 (0.726)</td>
<td>-0.433 (0.446)</td>
<td>-0.461 (0.652)</td>
<td>-0.522 (0.676)</td>
<td>-0.433 (0.614)</td>
</tr>
<tr>
<td></td>
<td>1.040*** (0.075)</td>
<td>1.040*** (0.366)</td>
<td>1.040*** (0.248)</td>
<td>0.915*** (0.012)</td>
<td>0.965*** (0.047)</td>
<td>1.040*** (0.077)</td>
</tr>
<tr>
<td>T1 (Year 2000)</td>
<td>-0.486 (1.575)</td>
<td>-0.486 (1.809)</td>
<td>-0.486 (2.205)</td>
<td>0.000*** (0.000)</td>
<td>-2.022*** (0.338)</td>
<td>-0.484 (1.485)</td>
</tr>
<tr>
<td>Group A</td>
<td>-0.001 (0.001)</td>
<td>-0.001 (0.002)</td>
<td>-0.001 (0.001)</td>
<td>0.000*** (0.000)</td>
<td>0.292*** (0.024)</td>
<td>-0.001 (0.001)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>0.352 (0.391)</td>
<td>0.352 (0.559)</td>
<td>0.352 (0.418)</td>
<td>0.000*** (0.000)</td>
<td>0.352 (0.389)</td>
<td>0.000 (0.000)</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>-0.000 (0.000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Notes: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.

Table S41: Sensitivity Analysis – regression results (dependent variable: teenage pregnancy; long term; Group A)

<table>
<thead>
<tr>
<th>Clustering Alternatives</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relaxing the restriction of using only counties with unexplored hydropower potential as controls</td>
<td>Without covariates (temperature, precipitation, royalties and state GDP)</td>
<td>Adding a covariate (population)</td>
</tr>
<tr>
<td><strong>Main Model</strong></td>
<td><strong>A</strong></td>
<td><strong>B</strong></td>
<td><strong>A</strong></td>
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<td>Standard errors clustered by county:</td>
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<td>Yes</td>
<td>No</td>
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<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
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<td>Yes</td>
<td>Yes</td>
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</table>

Ψ (Group A/ Long-term)

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1.001 (0.680)</td>
<td>-1.001 (0.616)</td>
<td>-1.001*** (0.355)</td>
<td>-1.214* (0.686)</td>
<td>-1.087 (0.660)</td>
<td>-1.013 (0.672)</td>
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<tr>
<td></td>
<td>0.147 (0.185)</td>
<td>0.147 (0.302)</td>
<td>0.147 (0.253)</td>
<td>0.560*** (0.060)</td>
<td>0.426*** (0.039)</td>
<td>0.169 (0.173)</td>
</tr>
<tr>
<td>T2 (Year 2010)</td>
<td>-1.745*** (0.392)</td>
<td>-1.614125</td>
<td>-1.745 (1.555)</td>
<td>-2.424*** (0.341)</td>
<td>-2.838*** (0.330)</td>
<td>-1.662*** (0.374)</td>
</tr>
<tr>
<td>Group A</td>
<td>0.000 (0.001)</td>
<td>0.000 (0.001)</td>
<td>0.000 (0.001)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.001)</td>
<td>0.000 (0.001)</td>
</tr>
<tr>
<td>Precipitation</td>
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<td>0.368 (0.282)</td>
<td>0.368* (0.217)</td>
<td>0.051 (0.042)</td>
<td>0.368** (0.144)</td>
<td>0.368** (0.144)</td>
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<tr>
<td>Air Temperature</td>
<td>-0.000 (0.000)</td>
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<td></td>
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Notes: ***Significant at the 1 percent level; **Significant at the 5 percent level; *Significant at the 10 percent level.
Table S42: Sensitivity Analysis – regression results (dependent variable: teenage pregnancy; short term; Group B)

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<td><strong>Main Model</strong></td>
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</tr>
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<td>Standard errors clustered by county:</td>
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</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
</tr>
</tbody>
</table>

| **Ψ (Group B/ Short-term)** | -0.015 (0.227) | -0.015 (0.411) | -0.015 (0.300) | -0.252 (0.281) | -0.202 (0.265) | -0.006 (0.226) |
| **T2 (Year 2010)**          | -0.080592 | -0.368 (0.411) | -0.368 (0.260) | -0.478*** (0.019) | -2.262*** (0.298) | -2.815*** (0.133) |
| **Group B**                 | -4.987** (2.340) | -4.987** (2.405) | -4.987** (2.410) | -0.001*** (0.000) | -0.001*** (0.000) | -0.000 (0.001) |
| **Precipitation**           | -0.000 (0.001) | -0.000 (0.001) | -0.000 (0.001) | -0.001*** (0.000) | -0.001*** (0.000) | -0.000 (0.001) |
| **Air Temperature**         | -0.342 (0.356) | -0.342 (0.369) | -0.342 (0.248) | 0.061 (0.059) | -0.349 (0.362) | -0.349 (0.362) |
| **Population**              | -0.000 (0.000) | -0.000 (0.000) | -0.000 (0.000) | -0.000 (0.000) | -0.000 (0.000) | -0.000 (0.000) |

Notes: ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.

Table S43: Sensitivity Analysis – regression results (dependent variable: HIV cases; short term; Group A)

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</tr>
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<td><strong>Main Model</strong></td>
<td><strong>A</strong></td>
</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
</tr>
</tbody>
</table>

| **Ψ (Group A/ Short-term)** | 3.392 (9.061) | 3.392 (9.557) | 3.392 (4.860) | 3.719 (7.813) | 4.335*** (0.373) | 3.210 (7.896) |
| **T1 (Year 2000)**          | 4.533* (2.308) | 4.533** (2.012) | 4.533* (2.706) | 4.876*** (1.065) | 3.921 (2.575) |
| **Precipitation**           | 0.004 (0.024) | 0.004 (0.023) | 0.004 (0.012) | 0.000 (0.001) | 0.030 (0.024) |
| **Air Temperature**         | 1.335 (6.063) | 1.335 (6.885) | 1.335 (4.553) | -0.328 (0.536) | 1.168 (6.189) |
| **Population**              | 0.000** (0.000) | -0.000 (0.000) | -0.000 (0.000) | -0.000 (0.000) | -0.000 (0.000) |

Notes: ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.
Table S44: Sensitivity Analysis – regression results (dependent variable: HIV cases; long term; Group A)

<table>
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<td>Standard errors clustered by county:</td>
<td>Yes</td>
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<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
</tr>
</tbody>
</table>

| T2 (Year 2010) | 3.419 (5.737) | 3.419 (5.009) | 3.419 (6.720) | 5.654*** (0.317) | 8.826*** (3.259) | 2.635 (5.810) |
| Group A | 3.638 (21.169) | 3.638 (24.141) | 3.638 (41.223) | 15.402** (6.743) | 15.755** (7.950) | 0.607 (22.079) |
| Precipitation | 0.005 (0.022) | 0.005 (0.027) | 0.005 (0.016) | -0.001 (0.002) | 0.005 (0.022) | 6.846 (7.409) |
| Air Temperature | 6.830 (7.369) | 6.830 (7.961) | 6.830 (5.766) | 0.528 (0.711) | 0.005 (0.022) | |
| Population | 0.000* (0.000) | 0.000* (0.000) | |

Notes: ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.

Table S45: Sensitivity Analysis – regression results (dependent variable: HIV cases; long term; Group B)

<table>
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</tr>
<tr>
<td>Standard errors clustered by county:</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard errors clustered by hydropower plant:</td>
<td>Yes</td>
</tr>
<tr>
<td>County and Year Fixed Effects</td>
<td>Yes</td>
</tr>
</tbody>
</table>

| Ψ (Group B/Short-term) | -3.307 (3.788) | -3.307 (3.305) | -3.307 (2.952) | -0.127 (1.515) | -3.701 (4.378) | -3.130 (3.754) |
| T2 (Year 2010) | 4.832 (5.392) | 4.832 (3.353) | 4.832 (2.555) | 1.862*** (0.100) | 4.947 (3.945) | 5.223 (5.575) |
| Group B | -17.795 (18.085) | -17.795 (16.075) | -17.795 (23.729) | -22.510*** (0.992) | -18.187*** (2.189) | -18.008 (18.372) |
| Precipitation | 0.006 (0.011) | 0.006 (0.009) | 0.006 (0.006) | 0 | 0.006 (0.011) | |
| Air Temperature | 0.166 (2.979) | 0.166 (2.525) | 0.166 (2.442) | -0.403** (0.177) | 0.035 (3.101) | |
| Population | -0.000 (0.000) | -0.000 (0.000) | |

Notes: ***Significant at the 1 percent level;**Significant at the 5 percent level;*Significant at the 10 percent level.
8.1. Introduction

This document includes details about the data and methods described in Chapter 4, as well as complementary results and discussion. We provide additional details about the government database used to model the Brazilian system and the method employed to build the baseline and alternative scenarios. We also describe in more details the hydrothermal scheduling issue and the SDDP algorithm applied to solve the electricity optimization problem. Further, we describe the method developed to produce wind time series from reanalysis data and its validity.

8.2 Detailed description of the baseline and alternative scenarios

To model the Brazilian electric system we used a database developed by Empresa de Pesquisa Energetica (EPE). EPE is the state company responsible for creating the long-term Brazilian energy plans. Every year, EPE issues an expansion plan (Plano Decenal de Energia) assessing the current and future energy infrastructure. One of the products from this plan is a set of files containing the characteristics of the Brazilian electric system, including demand projections, the major transmission lines, and the details about each power plant used to model the hydrothermal operation planning of the current and future system (EPE 2015). Those files are the inputs of the optimal operation model used by the government called NEWAVE. We downloaded the NEWAVE files from the EPE website and imported those files to SDDP.

Here, we present the main details about EPE’s 2015 report files and the method applied to build the alternative scenarios. Note, however, that we are still summarizing part of the information. For example, we are not presenting the details about the hydrology of each flow
gauge station associated with each hydropower plant. However, those details are available upon request to the paper authors.

### 8.2.1 Current System (May 2013)

The EPE’s 2015 report files represent most of the current Brazilian interconnected electric system (SIN) as of May 2013, and contain 133 hydroelectric power plants (86 GW) and 99 thermal power plants (20 GW). Other renewables like wind, biomass, and small hydro account for less than 10 GW. Table S1 describes the hydropower plants in operation in May 2013 (initial system) and their major characteristics. Table S1 also includes 10 reservoirs and water structures without power capacity that are part of the system.

**Table S1 - Hydropower plants in operation (May, 2013): major characteristics**

<table>
<thead>
<tr>
<th>ID</th>
<th>Name</th>
<th>Number of units</th>
<th>Installed Capacity (MW)</th>
<th>Average production coefficient (MW/m³/s)</th>
<th>Max. Turbined flow (m³/s)</th>
<th>Volume (Hm³)</th>
<th>Reservoir Area (km²)</th>
<th>Subsystem</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>Camargos</td>
<td>2</td>
<td>46</td>
<td>0.18</td>
<td>220</td>
<td>792</td>
<td>54</td>
<td>pa</td>
</tr>
<tr>
<td>2</td>
<td>Itutinga</td>
<td>4</td>
<td>52</td>
<td>0.24</td>
<td>236</td>
<td>11</td>
<td>2</td>
<td>pa</td>
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<tr>
<td>3</td>
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<td>3</td>
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<td>304</td>
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<td>0.75</td>
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<td>22950</td>
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<td>10</td>
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<td>4040</td>
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<td></td>
<td>Location</td>
<td>Area (ha)</td>
<td>Depth (m)</td>
<td>Discharge (m³/s)</td>
<td>Pressure Loss (Pa)</td>
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The hydropower plants are organized according to the cascade structure. In other words, hydropower plants from the same watershed/water system are arranged from upstream to downstream. Figure S1 shows an example of cascading structure for the São Francisco watershed.
hydropower plants. The cascade structure is crucial information for hydrothermal electricity system modeling because the reservoirs with storage located upstream have the ability to regulate the water flow for the power plants downstream optimizing the energy production.

Figure S1 - Hydropower plants cascade structure of the São Francisco river. Circles represent run-of-river hydropower plants and triangles represent hydropower plant with storage capacity. Blue represents existing plants and white/blue represent future plants.
Table S2 describes the main characteristics of the 99 thermal power plants in system in May 2013, including the marginal operational costs and emission factors. The marginal cost of electricity is defined in the EPE’s database based on the reports from the generators and it is used to define the dispatch order and thermal operation costs in the optimization.

Table S2 - Thermal plants in operation (May, 2013): major characteristics

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In the EPE model, hydro and thermal power plants are modelled individually. However, other renewables such as wind, small hydropower plants, and biomass are modelled as a group in each subsystem. Figure S2 projects the average renewable generation output by subsystem according to the EPE’s report files. Thus, the renewable generation in May 2013 is represented by the output defined in the first month of Figure S2. Figure S2 also presents the renewable generation projection to 2028. The different renewable sources explain the distinct generation output profile over time in Figure S2. For instance, most of the renewable generation in the Southeast is from sugar cane bagasse so the harvest seasons explain the generation peaks and valleys. Similarly, wind generation occurs mainly in the South and Northeast subsystems, which have larger variability in output associated with seasonal wind speed profiles. The North, Acre-
Rondônia, and Tapajos-Teles Pires subsystems include some small hydropower plants but there is limited capacity expansion in these subsystems by 2028 in the baseline scenario.

![Graphs showing renewable energy output for different regions](image)

**Figure S2 - Small renewables (Wind, small hydro, and biomass) expansion in the baseline scenario. Projected average output per month.**

We improved EPE’s modelling features for wind generation by replacing the fixed monthly output defined in the Northeast and South subsystem (Figure S2) by wind generation series created using wind speed data from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (Saha et al. 2016) for the current and future wind parks.
Table S3 presents the major characteristics from wind parks in operation in December 2014. Although the system simulation starts in May 2013, we represented the system from May 2013 to December 2014 in the baseline using the parks defined in Table S3. We applied this simplification because we were not able to rebuild the schedule of the wind parks that enter in operation from May 2013 to December 2014. Therefore, the wind parks in operation in December of 2014 represent the system in the first 17 months of operation and no additional wind is included during this period for the baseline. We simulated wind parks listed in Table S3 using NCEP-CSFR wind speeds and creating 32 years of hourly generation series for each plant. We aggregate the results by subsystem and demand block to create the inputs to SDDP.

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*Subsystems: su - South, no - Northeast*
8.2.2 Expansion scenarios

Table 4-3 in the Chapter 4 summarizes the additional power capacity in relation to the system in May 2013 for the baseline and alternative scenarios. The details about the baseline schedule for each hydroelectric and thermal power plant are described in the Annex C1. In the case of the future wind parks, they are represented by groups of 25 dummy parks with 30 MW of installed capacity each. Thus, each group contains 750 MW of installed capacity. To obtain the number of groups included per year, divide the power capacity per year described in Table 4-3 (Chapter 4) by 750. For instance, in 2028, the baseline scenario includes 2250 MW of additional wind capacity, divided in three groups of 750 MW. We defined the wind groups schedule by including one group per month in a given year. For example, if four groups are projected for the 2015 baseline agenda, the schedule will go from January to April (750 MW per month).

We created a total of 109 different wind groups to model the wind capacity in the baseline and alternative scenarios. The location of each power plant (with 30 MW) from this group was selected using a lottery with replacement based on the location sample of 1065 future wind parks. Figure S3 defines the location of the sample of 1065 wind parks. Furthermore, each group of 750 MW is subdivided in two subsystems: South and Northeast.
Figure S3 - Spatial distribution of wind parks under initial stages of development
8.3 Hydrothermal scheduling and SDDP characteristics

The objective of hydrothermal scheduling is to determine the sequence of hydroelectric dispatch, which minimizes the expected thermal operation cost (given by fuel cost plus penalties for rationing) along the planning horizon (PSR 2014). A decision tree described in Figure S4 illustrates the stochastic hydrothermal scheduling problem. Figure S4 shows that the system operator has two options: use hydro today or save water in the storage hydroelectric reservoirs. The top branch indicates that if hydroelectricity is used today and future inflows are high, the system operation is efficient because reservoir storage can be recovered. In contrast, if a drought occurs in the future, it may be necessary to dispatch more expensive thermal generation, or even interrupt load supply. The bottom branch implies that if storage levels are kept high through a more intensive use of thermal generation today, and high inflows occur in the future, reservoirs may spill, wasting energy and resulting in higher operation costs. Lastly, if a dry period occurs in the bottom branch, the storage will displace expensive thermal or avoid rationing in the future (PSR 2014).
Linear programming (LP) algorithms could, in principle, solve the system optimization problem described in Figure S2 (PSR 2014). However, the actual scheduling problem involves several hydro plants and, like our case, a study horizon of several years. Due to the exponential increase of inflow branches with time and number of plants, the resulting stochastic optimization problem quickly becomes computationally infeasible (“curse of dimensionality”) (Pereira & Pinto 1991).

We used the multi-stage stochastic optimization tool applied to energy planning called SDDP (stochastic dual dynamic programming) to support the analysis of the expansion plans (Pereira & Pinto 1991; PSR 2014). SDDP is also the name of the algorithm behind the software (Pereira & Pinto 1991). Power Systems Research (PSR), a Brazilian company, developed the optimization tool, and provided it for this study. SDDP simulates the future behavior of the system under several hydrological scenarios and calculates a policy that minimizes a risk-adjusted cost-based objective function (Pereira & Pinto 1991; Gorenstin et al. 2004; PSR 2014). The solution algorithm decomposes the multi-stage stochastic problem into several one-stage sub
problems. Each sub problem corresponds to a linearized optimal power flow with additional constraints representing the hydro reservoir equations and a piecewise linear approximation of the expected future cost function (Pereira & Pinto 1991; Gorenstin et al. 2004; PSR 2014). Each sub problem is solved by a customized network flow/Dual Simplex algorithm (Gorenstin et al. 2004).

Figure S5 illustrates the one-stage optimization problem. The basic idea behind the optimization is to minimize the immediate cost (ICF) and the future cost (FCF) subject to the operating constraints through the study horizon. The ICF decreases as more hydroelectricity is used today (stage $t$), which means that more water is passing through the turbines and less water is available in the storage reservoirs. On the other hand, FCF increases as more hydropower is dispatched and less water will be stored to supply the future demand leading to the use of more expensive thermal generation in the future. The FCF reflects the expected thermal generation expenses from stage $t+1$ to the end of the study horizon (PSR 2014).

![Figure S5 - Immediate and future cost functions versus outflow through hydroelectric turbines. The higher the outflow, the lower is the amount of water stored within hydroelectric reservoirs (Source: adapted from (PSR 2014)).](image-url)
Formally, Equation S1 defines the objective function.

\[ \text{Min } ICF + FCF \quad (S1) \]

The FCI is given by the sum of the thermal costs \( c(j) \times g_{t_k} \), in stage \( t \), plus penalties for operating constraint violations (PSR 2014). Equation S2 defines the immediate cost function

\[ ICF = \sum_{k=1}^{K} \sum_{j=1}^{J} c(j) \times g_{t_k}(j) + c_\delta \times \delta_{gt} \quad (S2) \]

where

- \( k \): indexes load block in the stage
- \( K \): number of load blocks
- \( j \): indexes thermal plants
- \( J \): number of thermal plants
- \( c(j) \): operating cost of plant \( j \)
- \( g_{t_k}(j) \): energy production of plant \( j \) in stage \( t \), block \( k \)
- \( c_\delta \): generic representation of operating constraint violation cost
- \( \delta_{gt} \): violation amount in stage \( t \) violation \( u \)

The solution of the FCF approximation is the main advance from the SDDP algorithm (Pereira & Pinto 1991). The future cost function, which depends on storage levels and past stream flows (Equation S3), is represented as a set of linear constraints, each one representing a segment of the piecewise linear function (PSR 2014).
\[ FCF = \alpha_{t+1}(v_{t+1}, \alpha_t) \]  

(S3)

where

\[ v_{(t+1)}: \text{final storage vector in stage } t \]

\[ \alpha_t: \text{lateral inflow vector in stage } t \]

The SDDP solution of the FCF is essentially composed of two phases: backward and forward. The backwards pass derives its name from the fact that during its execution, the algorithm solves one-stage problems in reverse chronological order. The solution of a problem at stage \( t \) is used to generate a cut, i.e., a supporting hyper plane, providing an approximation to future costs associated with decisions taken at stage \( t+1 \) (Rebennack, Flach & Pereira 2012; PSR 2014). Once the algorithm has progressed to the first stage, the forward phase performs a Monte Carlo simulation by solving one-stage problems taking into account the previously calculated cuts. The solution of the backward phase results in a lower bound of the future cost function. In contrast, the sum of the costs along the horizon given by the problems solved during the forward simulation results in an upper bound estimate (Rebennack, Flach & Pereira 2012; PSR 2014). All the details about SDDP algorithm are presented in the SDDP method manual (PSR 2014).

The optimization also takes into account all system constraints, such as water balance (inflows and outflows from each reservoirs), storage limits, loads (electricity demand), minimum and maximum outflow restrictions (e.g. for navigation or environmental purposes) and the thermal generation limits (PSR 2014). We follow the system constraints defined by in the EPE’s 2015 report files. The use of optimization tools, like SDDP, is a key factor to represent, study and plan any electric system with hydropower reservoirs.
8.4 Using reanalysis data to create wind electricity output scenarios

The EPE modeling approach defines wind generation as “must-run” power plants that follow an electricity output projection that represent the average wind seasonal variability (South and Northeast subsystems in Figure S2). The wind park representation adopted by EPE to characterize the wind electricity output in the 2023 expansion plan is very basic, and a key model limitation because it disregards the stochastic features of wind, as well as daily variability. To overcome this limitation, we created wind generation series for current and future wind parks.

The SDDP interface allows the incorporation of renewables variability in the optimal dispatch optimization through the inclusion historical records or data produced by an external model (“renewables scenarios”). SDDP assumes that the energy production in renewable plants is variable, but independent from one stage to the next. In other words, there is zero serial correlation. Before the iterative process of operating policy calculation starts, SDDP determines the scenarios to be used as follows: for each stage $t$ and for each conditioned inflow (“opening” in the backward recursion), a renewable energy production scenario is randomly sampled from the renewable scenarios. Those scenarios are then used in the backward phase. The forward simulation phase use the same scenarios sampled in the backward phase. If the number of forward series is higher than the number of openings, a “carrousel” scheme is applied (PSR 2014).

We created wind generation series using wind speed data from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (Saha et al. 2016) for the current and future wind parks. CFSR is an atmospheric reanalysis product available at an hourly time resolution from 1979 to the present and a horizontal resolution of 0.5° latitude.
× 0.5° longitude. Several studies assessed the characteristics, uncertainty and biases of using reanalysis CSFR to wind-power simulation but they are restricted to the United States (Rose & Apt 2015; 2016), Portugal (Carvalho, Rocha, Gómez-Gesteira & Santos 2014b), United Kingdom (Sharp et al. 2015), of-shore of the Iberian Peninsula Coast (Carvalho, Rocha, Gómez-Gesteira & Santos 2014a), and the Tibetan Plateau (Bao & Zhang 2013). Table S5 summarizes the main characteristics of those studies and their main findings.

### Table S4 - References about the use of wind speed NCEP-CSFR reanalysis

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<th>Study</th>
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<th>Study characteristics</th>
<th>Major results related to CSFR</th>
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<td>Rose and Apt, 2015</td>
<td>United States Great Plains</td>
<td>The authors developed a model that quantifies the uncertainties across many sites and corrects for biases of the reanalysis data. They applied this model to 32 years of reanalysis data for 1002 plausible wind-plant sites to estimate variability of wind energy generation and the smoothing effect of aggregating distant wind plants.</td>
<td>The authors find that coefficient of variation (COV) of annual energy generation of individual wind plants in the Great Plains is 5-12%, but the COV of all those plants aggregated together is 3.0%.</td>
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<tr>
<td>Rose and Apt, 2016</td>
<td>United States Great Plains</td>
<td>The authors developed a model of the bias and uncertainty of CFS reanalysis wind speeds.</td>
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<td>Carvalho et. al, 2014</td>
<td>Portugal</td>
<td>The authors compared wind simulation and wind energy production using several reanalysis dataset (including the NCEP-CSFR) and compared with observed data.</td>
<td>The comparison between NCEP-CSFR wind speeds and empirical data indicates root mean squared error of 2.19 m/s and correlation coefficient of 0.78.</td>
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<tr>
<td>Carvalho et. al, 2014</td>
<td>Iberian Peninsula coast</td>
<td>The authors compared off-shore wind simulation using several reanalysis datasets (including the NCEP-CSFR) and compared with buoy observed data.</td>
<td>The comparison between NCEP-CSFR wind speeds and empirical data indicates root mean squared error of 1.85 m/s and correlation coefficient of 0.86.</td>
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<tr>
<td>Sharp et al., 2015</td>
<td>United Kingdom</td>
<td>The authors evaluated the NCEP CFSR reanalysis model for hourly wind speeds by comparing the data against 264 onshore and 12 offshore weather.</td>
<td>The comparison between NCEP-CSFR wind speeds and empirical data indicates a root mean squared error that vary from 1 to 8 m/s depending on the measuring station but most of the results fall between 1 and 4 m/s. The correlation coefficient varies from 0.57 to</td>
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Table S4 indicates that NCEP-CSFR reanalysis wind data quality have been discussed in several studies, however, we did not find any reference that focused on Brazil or South America. Although the main objective of this study is not to assess the quality of using NCEP-CSFR reanalysis wind data in Brazil, we obtained wind generation data from 31 wind parks in Brazil, and we compared the real generation output from those wind parks against wind generation simulated using NCEP-CSFR wind speeds.

**8.4.1 Simulating wind electricity output using NCEP-CSFR wind speeds**

We obtained wind generation data from 31 wind parks owned by *CPFL Renováveis*, a company that develops and operates a renewable portfolio in Brazil. The data corresponds to hourly generation outputs from October 2014 to October 2015. We used the CPFL data to evaluate the application of NCEP-CSFR wind speeds as inputs to wind generation model (wind power function). Table S5 describes the main characteristics of CPFL wind parks.
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<tr>
<td>Taiba Albatroz</td>
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<td>2.1</td>
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</table>
First, we simulated wind generation for each wind park listed in Table S5 using NCEP-CSFR wind speeds from October 2014 to October 2015 (period of the real data). Specifically, we used the u and v components of the wind speeds at the layer between two “level at specified pressure differences from ground to level” (0,30 mbar). This layer corresponds to an average over the atmosphere up to the level where pressure is 30 mbar lower than at the surface (about 300 m up), which is approximately the height where the turbine rotors are located (roughly 150m up the ground depending on the wind structure).

Using the NCEP-CSFR wind speeds as inputs, we assessed four different wind generation models. The first two models are based on theoretical wind power functions: a cubic and an exponential. The power curves are defined in equation S4 and S5:

\[
q(v) = \frac{1}{2} \rho A C_p v^3 \quad - \text{Cubic} \quad \text{(S4)}
\]

\[
q(v) = \frac{1}{2} \rho A K_p (v^\beta - v_{ci}^\beta) \quad - \text{Exponential} \quad \text{(S5)}
\]

Where q is the energy output in Watts, A is the rotor area (m\(^2\)), \(\rho\) is the air density (kg/m\(^3\)); assumed 1.23), \(C_p\) is the power coefficients (assumed 0.4), \(v\) is the wind speed in (m/s) from NCEP-CFSR, \(v_{ci}\) is the cut-in wind speed in (assumed 5 m/s) and \(K_p\) and \(\beta\) are coefficients of exponential approximation (assumed 0.899 and 2.706, respectively) (Carrillo et al. 2013).
The other two models represent the wind power functions numerically. A wind power function has three key points: (i) cut-in speed below which the turbine will not produce power, (ii) rated speed at which the rated power of the turbine is produced, and (iii) cut-off speed beyond which the turbine is not allowed to deliver power (M. Brower: AWS Truewind, LLC & Albany 2009). The first non-parametric power function is a hyperbolic tangent (tanh) shaped curve built with a cut-in speed (c1, 3.5 m/s), a rated speed (c2, 11 m/s), and a cut-off speed (c3, 25 m/s). The second numerical representation of the wind power curves is based on three different composite power curves for each wind class developed by the Renewable National Energy Laboratory - NREL (M. Brower: AWS Truewind, LLC & Albany 2009). Table S7 defines the NREL composite power curves for a 2 MW turbines. For each site, we developed a code in R that choses the best composite power curve based on the wind speed averages of each site. When the generator capacity does not correspond to 2MW, we the figures in Table S6 scale up or down based on the wind park generator capacity. For example, Atlantica I wind park has 3MW generators, and, thus, we multiplied the composite power curve by 1.5 (3MW/2MW).
We evaluated the four wind generation models against the real data from CPFL wind parks calculating the Pearson correlation, the coefficient of determination ($R^2$) and the root mean square error (RMSE). The four-model comparison indicated that NREL composite power curves represent the most flexible and accurate model to transform wind speeds to electricity generation.
in Brazil without having the manufacturing details from the turbines. Thus, we assumed the NREL composite wind power curves as our reference to generate electricity outputs as a function of the NCEP-CSFR wind speeds.

Table S8 presents the correlation, $R^2$, and RMSE between the real data (CPFL wind parks) and model (NREL composite curves). The results are presented by hour, but we also aggregated the results by load block. As explained in Chapter 4, three load blocks represent the daily demand variability: high (6 p.m.-9 p.m.), medium (7 a.m.-6 p.m., and 9 p.m. - 12 p.m.), and low (0 a.m. - 7 a.m.).
<table>
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<th>Wind Park</th>
<th>Pearson Correlation</th>
<th>Coefficient of determination (R²)</th>
<th>RMSE (kWh)</th>
<th>RMSE (% of the maximum generation in the period)</th>
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<td>By hour</td>
<td>By block</td>
<td>By hour</td>
<td>By block</td>
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<td>0.83</td>
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</tr>
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<td>0.85</td>
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<tr>
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</table>

Statistics:
Table S8 shows that average hourly correlation between the real data and model varies from 0.5 to 0.75, which is within the same range found by the literature described in Table S5. The hourly $R^2$ results vary from 0.25 to 0.56 indicating that the model goodness of fit is modest. The RMSE results also indicate that difference between model and real data is significant (9% to 40% of the total generation capacity for one hour) for hourly predictions. However, when we aggregate the hourly results within the daily blocks and compare model and real data, the correlation, $R^2$, and RMSE improve significantly. The aggregation by block increases the average correlation from 0.62 to 0.90. Similarly, the average $R^2$ improves from 0.39 to 0.82, and the average RMSE (as a proportion of the total generation) decreases from 21% to 6%.

Therefore, the use of NCEP-CSFR wind speeds as inputs to the NREL power function model represents real data reasonably when generation is aggregated by block within the day.

The large improvement happens because although the model does not represent very well the hourly time series, it describes very well the hourly generation distributions. Figure S6 illustrates this idea. The top plot in Figure S6 shows the hourly time series comparison between model and real data for Morro dos Ventos III wind park. While it is possible to see some periods of good fit, other periods standout with noteworthy errors. The bottom plot shows a general hourly generation agreement between the real data and model histograms. Thus, the model describes very well the hourly data probability distributions such that when we aggregate the daily hours by three blocks, the errors between real data and model decrease significantly as shown by the statistics described in Table S8.
Figure S6 - Comparison between model vs. real data wind power output. Example for Morro dosVentos III Wind park. Top: Hourly generation time series. Bottom: Hourly histograms.

8.5 Costs

The Chamber of Electric Energy Trading (Câmara de Comercialização de Energia - CCEE, in Portuguese), which is the Brazilian electricity market operator, provides a dataset of all new power plants that sold energy in public auction since 2005 (CCEE 2015). This database contains the installed capacity and the forecasted capital costs for 826 power plants built from 2005 to 2015. Figure S7 contains the cost per unit of power histograms by fuel type.
We used the power plant construction costs from Figure S7 to estimate the capital costs for the baseline and alternative scenarios. Some power plants that are in the baseline scenario were already auctioned by the time of this study; thus, we applied the capital costs reported by the project itself. In the case of the future projects that did not go into auction yet, we estimated the capital costs according to the following assumptions:

- *Coal*: 2,440 reais/kW  
  (auction value for Pecem 1 project)

- *Diesel*: 1,040 reais/kW  
  (Diesel Projects average)
Large Hydro: based on installed capacity and calculated using the linear regressions described in Figure S8

Natural Gas: 2,100 reais/kW (NG Projects average)

Oil: 1,710 reais/kW (Oil Projects average)

Wind: 4,000 reais/kW (Wind Projects average)

Figure S8 - Capital Costs per kW versus installed capacity. Top: hydropower plants between 30 and 500 MW. Bottom: hydropower plants with more than 500 MW.

Tables S9 and S10 describe the estimated capital costs and maintenance costs. Annual operation and maintenance costs are estimated as 2% of the capital costs, which does not include the marginal fuel costs from thermal power plants (defined in Appendix A, table AS2). We
annualized the capital costs assuming a power plant lifetime of 50 years and internal rate of return of 12%.

Table S9 - Hydroelectric power plants costs

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<tr>
<th>Scenario</th>
<th>Name</th>
<th>Installed Capacity (MW)</th>
<th>Estimated construction cost (Reais/kW)</th>
<th>Total Construction Cost (million reais)</th>
<th>Annual O&amp;M (million reais)</th>
<th>Annualized cost (million reais)</th>
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|          | Hydropower plants replaced in scenarios Wind39 and Coal/Oil/diesel retirement |                         |                                       |                                        |                           |                                  |
|          | Belo Monte*             | 233                     | 1,693                                 | 395                                    | 8                          | 55                               |
|          | Belo Monte              | 11,000                  | 1,693                                 | 18,623                                 | 372                        | 2,615                            |
|          | Cachoeira do Caldeirão  | 219                     | 3,908                                 | 856                                    | 17                         | 120                              |
|          | Colider                | 300                     | 4,221                                 | 1,266                                  | 25                         | 178                              |
|          | Ferreira Gomes          | 252                     | 3,217                                 | 811                                    | 16                         | 114                              |
|          | Jirau                   | 3,750                   | 2,636                                 | 9,885                                  | 198                        | 1,388                            |
|          | São Manoel              | 700                     | 3,276                                 | 2,293                                  | 46                         | 322                              |
|          | Sinop                   | 400                     | 4,444                                 | 1,778                                  | 36                         | 250                              |
|          | Santo Antônio do Jari   | 370                     | 4,762                                 | 1,762                                  | 35                         | 247                              |
|          | Santo Antônio           | 3,151                   | 1,947                                 | 6,135                                  | 123                        | 861                              |
|          | Teles Pires             | 1,820                   | 1,829                                 | 3,329                                  | 67                         | 467                              |
|          | Replaced capacity before 2020 |                         |                                       |                                        |                           |                                  |
|          |                                                                 | 22,195                  | 47,132                                | 943                                    | 6,618                      |

|          | Total replaced capacity: scenarios B |                         |                                       |                                        |                           |                                  |
|          |                                                                 | 46,247                  | 108,658                               | 2,173                                   | 15,258                     |

|          | Non-Amazon reservoirs baseline |                         |                                       |                                        |                           |                                  |
|          | Água Limpa                  | 380                     | 3,366                                 | 1,279                                  | 26                         | 180                              |
|          | Apertados                  | 277                     | 4,113                                 | 1,139                                  | 23                         | 160                              |
|          | Arraias                    | 70                      | 4,327                                 | 303                                    | 6                          | 43                               |
|          | Baixo Iguacu               | 584                     | 3,458                                 | 2,018                                  | 40                         | 283                              |

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**Total Baseline** | **19,990** | **58,025** | **1,160** | **23** |
**Scenario C - NG** | **gas**     | **14,431** | **2,100** | **30,309** | **606** | **606** |

**Total Scenario C** | **34,423** | **88,334** | **1,767** | **629** |
References


### ANNEX C1 - Hydropower and thermal power plants schedule: Baseline scenario

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### Table AS2 - Detailed schedule and characteristics for thermal power plants in the baseline (NG= natural gas)

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