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Some important uncertainties related to climate change in projections for the Brazilian hydropower expansion in the Amazon

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A B S T R A C T

Brazil has an energy system with a hydrothermal characteristic that interconnects consumers and generators covering 98% of the demand for energy supplies. Most of the plants are concentrated in the southeast region, where the largest consumers and the largest population concentration are located. The expansion of this system, considering the hydroelectric contributions, will occur exploring the potentials located in the Amazon region. This analysis paper shows that the variations imposed by climate changes on some climatological variables create significant uncertainties about the power generation forecasts of the hydroelectric power plants to be installed in the Amazon, thus compromising the financial economic feasibility of these enterprises and also possibly compromising the expansion plans of the Brazilian energy system. The methodological approach uses information from various climate change scenarios and compares those with historical hydrological patterns and generation information. By exploring the characteristics of a large-scale hydrothermal system with high dependence on water resources, this paper provides valuable insights on how energy policy would address hydroelectric vulnerabilities and climate change. This analysis is focused on the Brazilian case but reveals important issues related to systems with hydro thermal characteristics.

1. Introduction

The assessment of the impacts of climate change on hydro power generation is not new, but the analysis and planning of the expansion in large energy systems still presents some challenges and few comprehensive studies are present in the literature. The operation and expansion of energy systems largely based on water resources is a particularly complex problem, because of the need to forecast the renewable resources available to obtain energy supplies. This paper contributes to this field, proposing a methodology that can be readily applied to large systems, particularly to systems with large contributions of hydro power plants, such as the Brazilian system and its expansion in the Amazon region.

Changes in Earth's climate have been studied for some decades and its causes may be associated with natural causes or the action of man or even by a combination of these two. Climate change refers to statistically significant variations in climatological variables (such as temperature, precipitation, evaporation, etc.) in relation to the respective mean values of historical series. Regardless of the causes, climate change can influence directly or indirectly the available flows for power generation in hydroelectric plants. The main contribution of this paper is an analysis of the influence of climate change on the flow of rivers in the Amazon that will be used in the coming decades to expand the Brazilian energy system.

Annual changes in precipitation, evaporation, and river flows are used to estimate the possible effects of climate change on energy supply forecasts and consequently on projections of financial revenues that can be obtained exploiting these resources for power generation. An accurate projection of the financial benefits obtainable with a hydroelectric power plant is essential to the justification of the project to investors and environmental authorities. This analysis will show that climate change scenarios insert significant uncertainties in the predictions of energy supplies and consequently in the revenue streams obtained with hydroelectric power plants operating in the Amazon region.

This analysis paper is composed of three sections, besides this Introduction. The next section describes the method proposed to relate the effects of climate change on the profits obtainable with

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Abbreviations

ANEEL National Electric Energy Agency, or "Agência Nacional de Energia Elétrica", in Portuguese
CCR Climate Change Research
CGCM2 The 2nd generation Coupled Global Climate Model
COD Centralized Optimal Dispatch
CSIRO2 Commonwealth Scientific and Industrial Research Organization, v.2
ECHam4 European Centre/Hamburg Model 4 Transient
EPE Energy Planning Enterprise, or "Empresa de Planejamento Energético", in Portuguese
GCM Global circulation model
HadCM3 Hadley Centre Coupled Model, v. 3
IPCC intergovernmental Panel on Climate Change
ONS Independent System Operator, or "Operador Nacional do Sistema", in Portuguese
PCM Parallel Climate Model
WMO World Meteorological Organization

Variables, units and dimensions

α [1] parameter relating future scenario and historial series for precipitation
β [1] parameter relating future scenario and historial series for evapotranspiration
γ [1] runoff coefficient
$\Delta_{REVENUE}$ percent change in revenue
ΔS [L] storage variation
ρ [kg/m3] water density
η [1] overall efficiency
$(\Sigma H/K)j$ [MW/m/s] sum of all the conversion factors associated with plant j
e [MWh] energy
esat [mb] saturation vapor pressure
ET [L] annual evapotranspiration
ET [mm/month] monthly potential evapotranspiration
ET0 [L] annual evapotranspiration, historical series
ET1 [L] annual evapotranspiration, future scenario
g [m/s2] acceleration due to gravity
H [m] head
$H_{downstream}$ [m] water level downstream of the reservoir
H_{loss} [m] head losses in the penstock
N [1] number of plants in the system
P [L] annual rainfall
P0 [L] annual rainfall, historical series
P1 [L] annual rainfall, future scenario
p [MW] power
PEi [MWd] total potential energy stored in the system at the beginning of month i
Q [L] annual runoff
Q0 [L] annual runoff, historial series
Q1 [L] annual runoff, future scenario
q [m3/s] flow rate corresponding to a given time of recurrence, based on Q values from flow duration curves
R [1] rate of change of surface runoff
T [°C] monthly average temperature
t [h] time period considered
Vij [hm3] volume of water stored in the reservoir j in month i

hydropower generation in some places in the Amazon and the subsequent sections respectively present and discuss the results and summarize the conclusions. This Introduction describes briefly the Brazilian energy system and its expansion in the Amazon, discussing some possible effects of climate variability and environmental changes.

An energy system interconnects consumers and generators covering 98% of the demand for energy supplies in Brazil. This system consists [1] (on February 4, 2017) of 1245 hydroelectric plants (64.65%), 2945 thermoelectric plants (27.12%) and 460 other plants (8.23%), including wind farms, photovoltaic plants and nuclear power plants. This system currently offers 151,632.24 MW [2], with a further 8453.91 MW under construction and 16,460.78 MW under licensing. Hydropower facilities are concentrated in the southeast region of Brazil, where most of economic activity and population is located.

Hydropower plants have the advantage of energy storage at a low cost compared to other alternatives for power generation. In addition, they work with lower greenhouse gas emissions. However, the availability of hydropower is limited by reservoir inflow, storage capacity and turbine flow capacity. The release of water for hydroelectric power generation or downstream consumption as well as water retention to increase supply reliability during drought seasons are influenced by these parameters. Keeping reservoir storage too high can result in unwanted spills, reducing hydropower availability, and increasing operating costs.

During normal rainfall years, the large hydroelectric reservoirs are able to store enough energy to supply the energy demand, taking into account the consumption peaks. The several existing run-of-river plants also help to meeting the demand. Power generation is directly linked to the flow rate in rivers, so this is usually not a problem during rainy years but it can be seriously affected in the drier years. The reservoirs add flexibility to the system by storing energy as water and compensating for temporal and spatial availability imbalances across the country.

Considering the different hydrological regimes throughout Brazil, seasonal power generation is transferred across subsystems, with the hydropower plants of the "wet" basins compensating the power generation required in the "dry" basins [3]. All the energy generated in each subsystem (Fig. 1, above) can thus be transmitted to the others, allowing the system to take advantage of the hydrological complementarity between different basins. The extensive interconnection of subsystems also allows the transfer of energy from one region with greater hydroelectric capacity to another dominated by (more expensive) thermal generation [4] reducing overall energy costs.

The spatial distribution and values of electricity production and demand by regions for the Brazilian energy system are represented in Fig. 1. For 2010, the system load was roughly 475,095 GWh with a supply of 476,352 GWh. The surplus was exported to Argentina, Paraguay and Uruguay [2]. The South and Southeast regions concentrate the largest industrial consumers and the highest population concentration. The Itaipu hydroelectric power plant is strategically located in relation to these regions. The Northeast also concentrates several industrial consumers and some large cities.

This figure shows schematically the main transmission lines between the South and Southeast regions, between the Southeast and Centre-West regions, between the Northeast and North regions and between these two last connections. There is also the Itaipu Power Plant and its important connection supplying the Southeast region. Isolated consumers from the North region are fed mainly with independent thermoelectric systems, with a small capacity for energy acquisition from Venezuela. This figure also shows that the Southeast, Centre-West and Northeast regions produce less than