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Climate change impacts in the energy supply of the Brazilian hydro-dominant power system

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ABSTRACT

Over the past few years, there has been a growing global consensus related to the importance of renewable energy to minimize the emission of greenhouse gases. The solution is an increase in the number of renewable power plants but unfortunately, this leads to a high dependence on climate variables which are already affected by climate change. Brazil is one of the largest producers of electricity by renewables through its hydro-dominant power generation system. However, hydro-generation depends on water inflows that are directly affected by climate change that consequently affect the electricity production. Therefore, these changes need to be considered in the operation and planning of a hydro-dominant power system. In this paper, we present the effects of different climate scenarios in the water inflows produced by the regional Eta climate model. Normally, studies use an optimization model to make decisions in case of a hydro-thermal scheduling problem and use the assured energy to evaluate the hydro-production. In this analysis, water inflows used in the optimization process consider different trends according to its associated climate scenario. Our paper shows that climate change may drastically impact the system assured energy and consequently, the system's capability to supply load.

1. Introduction

Renewable energy sources are helping countries around the world to reduce oil supply dependence and move towards a more environmentally friendly society. There are compelling reasons associated with sustainability and public health, and also good perspectives for investments in renewable energy technologies such as wind, solar, and biomass. New investments in renewables are essential to match future electricity demands without contributing to the threat of global warming. For example [1], examines the threshold effect of the proportion of the renewable energy supply needed to reduce CO_2 emissions, which is one of the main actions towards minimizing global warming. Fortunately, many countries utilize access to clean energy in their energy programs [2,3].

Strong evidence related to climate change [4,5] as well as the understanding of the importance to consider this information in different spheres [6] has emerged over the years. However, it is important to take into account the current, and potential future, climate changes due to global warming when analyzing renewables' penetration and planning a power system's generation capacity. Climate conditions directly affect renewables and consequently affect their electricity production. For example, hydro is a type of renewable energy source that has gained a steady success attracting investments over the years. Hydro energy production highly depends on the amount of water inflows, the "fuel" responsible for powering hydro turbines, available at each hydro power plant during a particular period of time. Furthermore, these water inflows depend on precipitation (climate variable) which is often represented in rainfall-runoff models [7,8]. In several places, precipitation analysis has presented a contrasting behavior over the years [9,11] when compared with historical data, which climate change could intensify even more in the future. Another related example can be seen in a system with a large share of wind

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Nomenclature

Abbreviations

- IPCC Intergovernmental Panel on Climate Change
- GCM Global climate model
- HadCM3 Hadley Centre coupled model from United Kingdom
- A1B Global climate change scenario from IPCC
- INPE Brazilian national institute for space research
- Eta-CPTEC Regional climate model developed by INPE in Brazil
- Eta-X Eta regional climate model with resolution of X km
- MGB large basin rainfall-runoff hydrological model
- HTSP Hydro-thermal scheduling problem
- EGS Existing generation system
- FGS Future generation system
- ISO Power system independent system operator
- EPE Brazilian federal energy planning company
- CO_2 Carbon dioxide
- GHG Greenhouse gases
- HIGH, MED, LOW, CTL Members from HadCM3 constructed from A1B climate scenario with different increases in global temperature
- HRU hydrological response units
- FUT_X 30-year periods starting in 2011 and going up to 2100, X = 01 (2011–2040), X = 02 (2041–2070), X = 03(2071–2100)
- GDP Gross domestic product
- SLP-T Stochastic linear program with T time stages
- PAR-*n* periodic autoregressive model of order *n*
- RE, PS, DM, FD Other water use scenarios, in order: country's economy in recession, country's economy in a process of stagnation, development of country's economy in a moderate proportion and country in a state of full social development

Indices and Sets

- $t \in T$ set of time periods and its associated index

Parameters

- c_t operational cost vector associated with power generation and curtailment costs at stage t
- b_t represents deterministic electricity demand and a specific realization of the stochastic water (or energy) inflows at stage t
- A_t model's structural constraint matrix at stage *t* that captures mass-balance, demand satisfaction, maximum hydro generation constraints and energy transfer constraints
- $B_t x_{t-1}$ represents the storage in the system that is carried forward from stage $t-1$ and is available at stage t

Decision Variables

- x_t decision vector to represent hydro generation, thermal generation, storage at reservoirs, and spills at stage t

Functions

- $h_{t+1}(\cdot)$ recursive function that represents a model like (4)–(6) where t is shifted by one unit. It depends on decisions made at stage t, and random parameters that are revealed at the beginning of stage $t+1$
- $\mathbb{E}_{b_{t+1}|b_t} h_{t+1}(x_t, b_{t+1})$ expected cost function of stage $t+1$ given decisions x_t, that were made in stage t, and the realization of the random parameter b_{t+1}

generation where changes in wind speed and wind direction impose vulnerability problems.

Therefore, in order to design a robust power system for the future, it is necessary to take into account different climate scenarios in the evaluation of renewable energy sources. For example, in [12] authors present a study of the impacts of global climate changes on the availability and the reliability of wind power in long-term energy planning for the Brazilian system. Impacts of global climate changes in terms of wind power density for selected sites can be found [13] and in terms of hydropower generation and liquid biofuels in [14]. In [15], climate change impacts in energy production of photovoltaic, wind and hydro power plants are evaluated in Croatia using climate data regionalized from a global climate model (GCM). Other studies present analysis of renewables as an alternative to mitigate climate change by reducing greenhouse gas emissions [16,17] from fossil fuel used by thermal power plants.

This paper presents significant advances from [18] in the assessment of climate change impacts in generation assured energy in Brazil. The available information from global climate change scenario A1B is downscaled by the regional Eta-CPTEC climate model [19]. Also, we have transformed climate variables, such as precipitation, that are outputs from this climate model into water inflows by using the large basin rainfall-runoff hydrological model (MGB) [7] for each hydro power plant site. The water inflows are then used as input in a mathematical optimization model to determine the generation assured energy for the whole power system, i.e. the system assured energy that can be defined as the total energy available in the system at a risk of 5% of not supplying the demand (the process to compute the system assured energy is further explained in Section 4.2). Based on the Brazilian regulation, individual values of generation assured energy can be obtained for each hydro power plant using the firm energy rights [38]. Such individual generation assured energy represents the maximum amount in which a hydro power plant can trade in the Brazilian electricity market. Finally, the sum of individual generation assured energy is equal to the system assured energy.

Given that the precipitation regime in some river basins may change, results from this work are crucial for the generation plan in terms of the placement of new power plants in the country. Additionally, this paper evaluates possible effects of different water use scenarios on energy production. Fig. 1 depicts the aforementioned steps of the procedure to assess the system assured energy. In this work, we consider the correct representation of the Brazilian power generation system described in Section 2.

A mathematical model that optimizes water resources and thermal plants generation is used to determine the system assured energy. This model aims to represent the hydro-thermal coordination, or hydro-thermal scheduling problem (HTSP) [21–24]. The HTSP is modeled over a planning horizon with a finite number of time stages, which are discretized on a weekly or monthly basis. One of the most important information related to HTSPs is the natural water inflow that is available at each hydro power plant at the beginning of each time stage of the planning horizon. Water

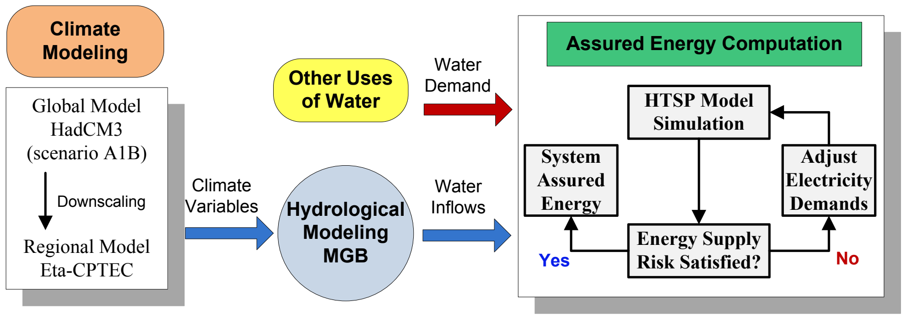

Fig. 1. Computation flowchart used to evaluate the system assured energy.

inflows are usually considered to be stochastic because of their dependence on the random precipitation behavior and it is common to assume that there exists a stochastic process that governs the realization of such parameters. Usually the stochastic process associated with future water inflows are assumed to be a stationary processes defined using historical data [25]. Due to the random nature of future water inflows, one's ability to make decisions regarding water use and thermal generation relies on mathematical formulations that approximate the true problem as a multi-stage stochastic linear program [22,23,26]. In this framework, one is interested in using generation resources (hydro and thermal) to satisfy system demand. The objective is to minimize the electricity production costs used to satisfy the demand during a specific time horizon. These costs are derived from the fuel costs used by thermal power plants and the possible expenses with demand curtailments.

The majority of methods used in the context of HTSPs that forecast water inflows use historical data, which usually have good performance, for short-term prediction. However, for long-term projections and analysis, these methods fail and simulation becomes a better option to determine possible future scenarios. This paper uses simulation results from climate variables provided by the global models presented in the Intergovernmental Panel on Climate Change (IPCC) [5]. The sequence of models that starts from the GCM and goes through regional downscaling, hydrological model simulations and finishes with the assessment of the system assured energy using a HTSP model represents a novel approach to identify future behavior of different climate patterns.

This paper is structured as follows. Section 2 describes the Brazilian interconnected power system and the configurations of this system that we use to carry out our analysis. Section 3 gives a general description of the climate and the hydrological modeling as well as the soil and water use scenarios. Section 4 presents the methodology used to evaluate the system assured energy for the Brazilian interconnected power system. Section 5 presents the results and discussions regarding different climate scenarios in other instances of the problem. Section 6 concludes this paper.

2. The Brazilian interconnected power system

The Brazilian interconnected power system heavily relies in hydropower [27], which is responsible for approximately 80% of the annual electricity production in the country. The power generation system is composed by hydro (reservoir storage, run-of-river, pumped-storage), thermal (natural gas, coal, diesel), nuclear and other renewable power plants. The majority of these power plants, which are connected to the system, are operated by the Brazilian independent system operator (ISO). The other renewables include small hydro (power plants with installed capacity smaller than 30 MW), biomass, wind and solar generation, which are not included in the HTSP optimization process. The current practice in Brazil is to subtract an average energy production from these other renewable sources from the electricity demand before the optimization takes place. The generation system is divided into four subsystems according to the main geographical regions in Brazil (Southeast/Midwest, South, Northeast, and North Region).

In our analysis we consider two distinct configurations of the Brazilian power generation system. One represents the condition of the Brazilian interconnected power system presented in January of 2012 [28], named existing generation system (EGS). The other is named future generation system (FGS) and represents a planned configuration designed by the Brazilian federal energy planning company (EPE), which is in charge of planning both the generation and the transmission systems in Brazil. The EGS total installed capacity is 113.6 GW composed of hydro (38.2% hydro with reservoir storage, 35.5% run-of-river hydro and 0.7% pumped-storage), thermal (16.3%) and other renewables (9.1%) [29]. The FGS has several new hydro power plants in the North subsystem where the Amazonas river basin is located. These new hydro power plants are expected to be in operation near the end of 2030 [29,30]. The FGS total installed capacity is 170 GW composed of hydro (31.7% hydro with reservoir storage, 34.8% run-of-river hydro and 0.5% pumped-storage), thermal (17%) and other renewables (16%) [31].

For the EGS (FGS) installed generation capacity, approximately 60% (46%) is located in the Southeast, 16% (14%) in the South, 14% (17%) in the Northeast and 10% (23%) in the North subsystem respectively. Subsystems are interconnected via transmission lines that enable energy optimization among the power plants and consequently, among the energy storage at the river basins. The exchange capacity between the subsystems depends on transmission lines' capacities, which are kept constant along the simulation, i.e., there is a set of capacities for the EGS and a set of capacities for the FGS. The last one incorporates the transmission expansion plan, also provided by EPE [31].

The proposed configuration of the FGS has ten subsystems instead of four, and two fictitious interconnection nodes (Imperatriz and Ivaiporã) as represented in Fig. 2. Fig. 3 shows a modified configuration that considers the aggregation of different subsystems to represent the FGS with four subsystems such as it is considered for the EGS. It is important to notice that the subsystems Paraná River, Acre/Rondônia, Teles Pires/Tapajós and Itaipu are added to the subsystem Southeast/Midwest, and subsystems Belo Monte and Manaus/Amapá were aggregated to subsystem North. These groupings were performed by analyzing the existence of interconnections (transmission lines linking subsystems).

3. Climate and hydrological modeling

3.1. Climate modeling and future scenarios representation

Climate models are used to mathematically represent natural

Fig. 2. Brazilian power system projected for year 2025.

Fig. 3. FGS power system configuration for HTSP model.

processes and their interactions within the atmosphere, land surface, ocean, and sea ice that can affect the weather and the climate at different time scales. These models quantitatively take into account the behavior of a set of components such as clouds, aerosols, vegetation, snow cover, soil water, solar radiation, and others to first simulate present climate conditions and then to project climate in the future. To use climate models for projections it is necessary to make assumptions about input factors that affect the simulation process, for example the future amount of carbon dioxide (CO_2) concentration in the atmosphere. Generally, such models are used to perform simulations of climate evolution scenarios considering various levels of greenhouse gas (GHG) emissions.

Studies and developments related to mathematical climate models are performed all over the world. By an initiative of the environmental program developed by the United Nations and the World Meteorological Organization, the IPCC was formed in 1998. The IPCC studies the current scientific knowledge of climate change and evaluates possible environmental and socio-economic impacts for society. Since then, the IPCC has been an important channel for the implementation of macro policies in response to climate change. In this work, among the various scenarios of GHG emissions on the horizon from 2000 to 2100, the A1B scenario was chosen because it represents an average growth of future CO_2 emissions, i.e., neither too high nor too low [5,19]. In this paper, our simulations are carried and based on the results of the IPCC report presented in [5].

The HadCM3 model developed by the United Kingdom Met Office Hadley Centre was chosen as the GCM that is followed in this paper. Many tests were made by the Brazilian National Institute for Space Research (INPE) to determine which GCM better represents the South American region in terms of climate simulation [19] and the HadCM3 model was the one that best fit the historical data. For the purpose of this work, four members of the HadCM3 constructed from temperature variations, using the A1B scenario, called High, Medium (MED), Low, and Control (CTL) were used [19]. These members can be interpreted as different increases in global temperature at the end of this century, that is, the High represents an increase of 6° C, the Medium of 4° C and the Low of 2° C. The Control member is the base case in which the increase of temperature is close to the one associated with the Medium member.

The HadCM3 model has a granularity of 400 km resolution, which cannot adequately represent, for instance, two sets of mountains of the Brazilian relief: Serra-do-Mar Mountains and Mantiqueira Mountains. There are important basins located in these mountains that need to be better represented by the model. Therefore, dynamic downscaling techniques [20] were employed through the use of regional climate models, which provide a more detailed spatial and temporal representation than the variables available in the global models. The combination of the regional Eta-CPTEC model downscaled from the HadCM3 GCM has shown to perform favorably against current climate models when representing South American regions [20,32].

The regional model Eta-CPTEC with 40 km resolution, or Eta-40, significantly improves the accuracy of global models. The Eta-40, calibrated for the South American region between 1960 and 1990, is employed in this paper which uses the results from simulations with this model [19]. The Eta-40 incorporates climate change due to CO_2 emissions and seasonal variation of vegetation for 360 days synchronized with the timing of the HadCM3 global model. The Eta-40 km is nested at the HadCM3 model. The four Eta-40 members: HIGH, MED, LOW, and CTL, are used in this paper to generate rainfall data. These represent the basic information used to define the behavior of the natural water inflows that will be available at each hydro power plant reservoir at each time stage of the HTSP. In order to test the accuracy of the regional representation, this paper uses a higher resolution of 20 km (Eta-20) for the CTL member to compete with the Eta-40 CTL [19].

3.2. Hydrological modeling for natural water inflows

The hydrological model MGB [7] is used to make the evaluation of the rainfall-runoff functions for each river basin of the system. MGB model includes the specific soil and vegetation characteristics of each represented region. It is based on the association and adjustment of two other hydrological models named LARSIM and

VIC [7]. The model is distributed in space, i.e., each river basin is separated into smaller units, called mini-basins, which are interconnected by the drainage system.

The MGB is composed of mathematical representations of interception, infiltration, soil water balance, evapotranspiration and drainage of the surface, sub-surface and groundwater flow. Each mini-basin is broken down into blocks called hydrological response units (HRU), which are generated by a combination of soil and vegetation maps. Each HRU is characterized by a set of parameters, such as maximum capacity of soil aquifer storage, leaf vegetation area, and others. The water balance is computed for each HRU and water inflow results are added and spread into the drainage system. The flow in each HRU does not instantly go into the drainage system, i.e., there is a specific time-constant within each mini-basin [7]. Precipitation, temperature, relative humidity, solar radiation, wind speed, and atmospheric pressure at each mini-basin are calculated through an interpolation using geo-referenced data.

Another important step is the calibration of hydrological parameters used to represent physical and historical features from similar river basins. The hydrological information considered in this work considers MGB calibration using monthly data ranging from 1960 to 2010. We apply MGB to define water inflows for the set of hydro power plants chosen to compose the power generation facilities obtained from [28,30], which was previously discussed in Section 2. Fig. 4 shows the main existing basins in Brazil with the representation of some hydro power plants along a cascade system inside each river basin.

The water inflows were generated by MGB calibrated for each river basin using the climate variables such as precipitation, wind, sunlight, temperature, humidity and atmospheric pressure from Eta-40 (members, LOW, MED, HIGH, and CTL), and Eta-20 (member CTL) as input data. For the same member CTL, two granularities were tested (Eta-40 km and Eta-20 km) in order to verify possible differences in terms of water inflows. After MGB runs, hydrographs were generated for all hydro power plants of interest in each 30-year simulation period used to represent past and future time periods. The time period of 30 years is used due to the extensive computational time and data storage required to perform Eta model simulations. Another important point is that the comparison of increase and decrease trends in water inflow rates is made for a period that represents the current conditions of the system.

Fig. 5 depicts three maps that translate water inflow results from MGB simulations using climate variables from Eta-20 member CTL for future periods one, two, and three (from left to right named FUT_01, FUT_02, FUT_03). These represent 30-year periods starting in 2011 and going up to 2100. The maps presented in Fig. 5 indicate future anomalies of the average water inflow in each hydro power plant of the Brazilian interconnected power system considering climate projections from the Eta-20 model. These maps show the simulated river basins where the dots indicate the geo-referenced position of a particular hydro power plant. The point size is proportional to the hydro power plant drainage area. Green points represent increase in future water inflows with respect to the base period (1960–1990) and red dots indicate reduction in water inflows with respect to the base period. The color intensity of each point is related to the rate of change in water inflows.

In general, there are trends of decreasing water inflows in future

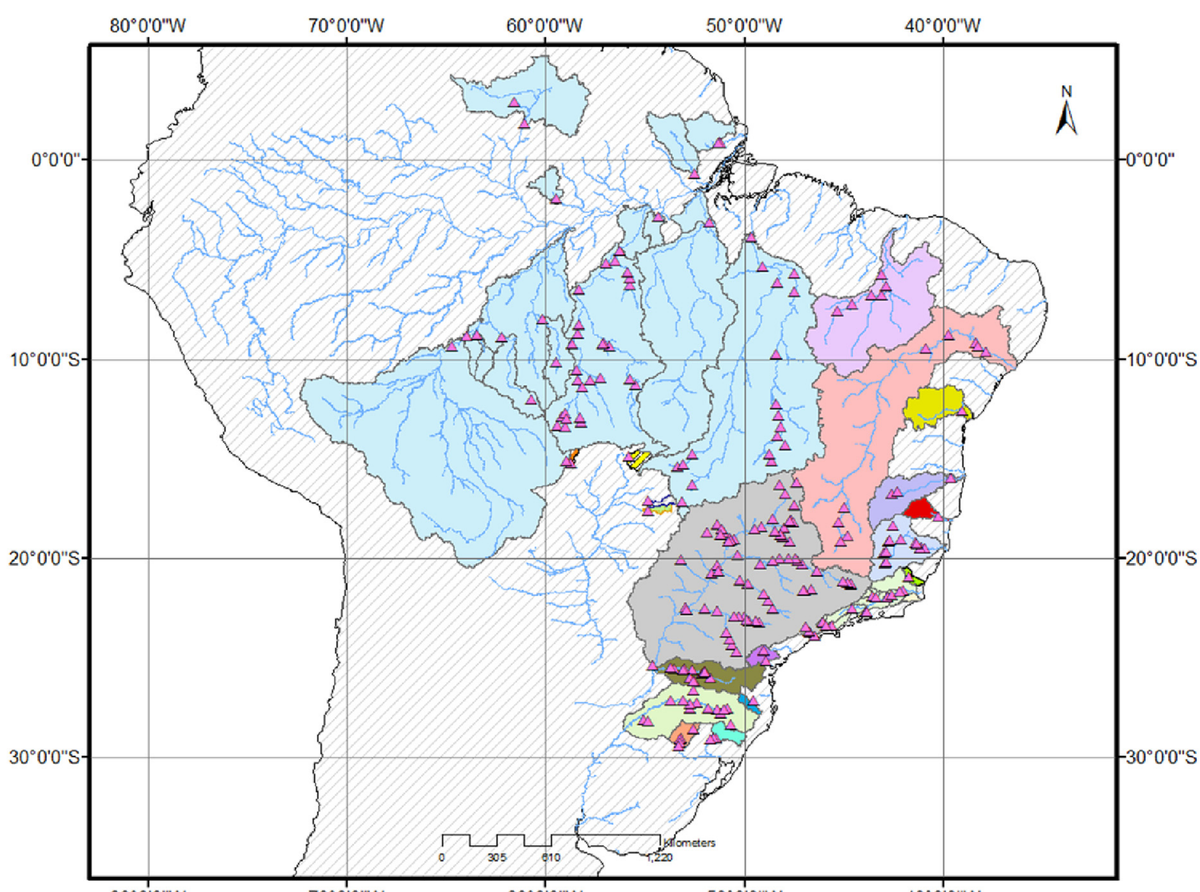

Fig. 4. River basins and the considered hydro power plants for hydrological modeling.

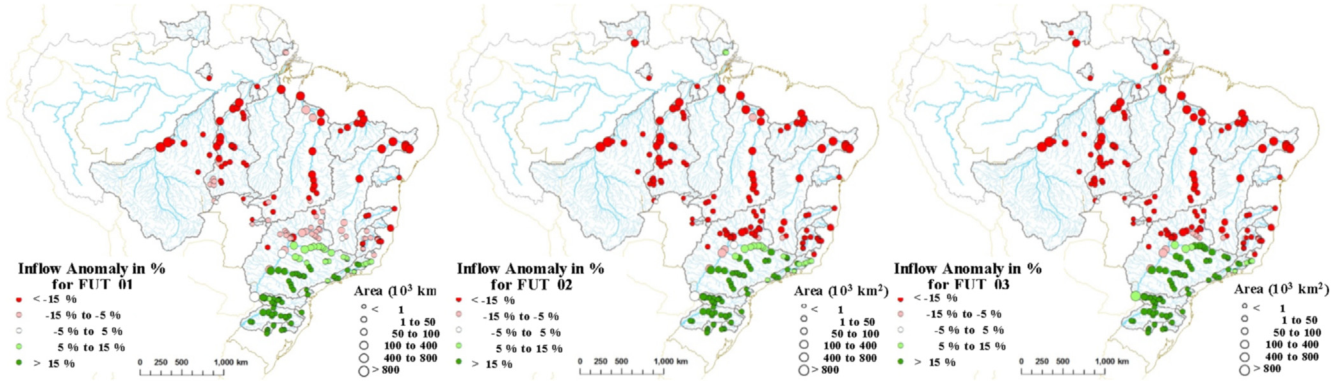

Fig. 5. Water inflows future variation for each future period with respect to the base period.

periods in both the North and Northeast regions of the country. The South and the Southeast regions present an increasing trend in water inflows for most of the hydro power plants. The time intervals FUT_02 and FUT_03 present the largest decrease in water inflows in the North and Northeast regions of the country. Water inflows for the different periods have similar patterns as the climate variables produced by Eta models, particularly, the precipitation.

3.3. Other water uses

In order to also consider the evolution of water consumption along each river basin in this study, four evolutionary scenarios were built representing the Brazilian economic development in four different perspectives: a pessimistic situation (country facing a recession), an optimistic situation (country under full development) and two intermediate situations (country in a stagnation condition and country facing a moderate development). These scenarios were created in [33] following a spatial and temporal representation of water usage in the country [34] adapted according to the national plan of water resources from [35] and data from the Brazilian Institute of Geography and Statistics [36].

The scenario that represents the country's economy in recession corresponds to a situation in which the world is in recession and Brazil does not overcome its basic infrastructure bottlenecks, institutions have an inefficient performance, the water resources management system is not properly or completely implanted and conflicts over water use remain and may increase. In terms of sanitation, a significant loss of water is represented which generates a high per capita consumption. In this scenario, the irrigated agricultural development is modest which leads to a search for new agricultural areas. The industry-performance is weak with a gross domestic product (GDP) decreasing around 2% per year. Agricultural production in this scenario is destined for the domestic market because the competitive conditions and compliance with the requirements of the most demanding markets with respect to sustainability are not present.

The scenario representing process of stagnation for the country's economy considers a situation in which the country cannot be inserted into the growing world. The difficulties observed in the recession scenario remains with the aggravation that the world's economy is growing. In this case, agricultural production may be required by other less demanding markets with respect to sustainability, leading to over-exploitation of natural resources to satisfy external demand related to specific crops cultivation.

The scenario that represents a development of the country's economy in a moderate proportion considers a condition in which the world is in recession but the country in analysis has solved its infrastructure problems. The internal market conditions guarantee economic growth and demand development of crops linked to the increase in purchasing power. Sanitary conditions significantly improve reducing water consumption and distribution losses. Also, the water management system is implanted and it is fully operational with anticipation and reduction of conflicts over water use. The country's institutions operate in normal conditions increasing the safety of the productive sector.

The last scenario represents the country in a state of full social development integrated with economic growth. In this scenario, the country finds its niche in the international market without giving up the sustainable use of its natural resources. Agricultural development is able to supply the domestic and other foreign markets. For more details about the representation of the other water uses and their impacts on the water inflows, the reader should refer to [33].

4. System assured energy computation

This paper's interest is in evaluating the system assured energy instead of individual values for each hydro power plant. The system assured energy is calculated after performing simulations of a HTSP model [18,37]. In Subsection 4.2, the procedure to define HTSP simulation results and the process to obtain the system assured energy are explained.

4.1. Hydro-thermal scheduling problem

In the HTSP, the main goal is to find a schedule for hydro and thermal power generators at each time stage during a specific planning horizon in order to satisfy electricity demand while minimizing operational costs. A *T*-stage stochastic linear program (SLP-*T*) with recourse, to represent the HTSP, may be formulated as follows:

$$\min_{x_1} c_1 x_1 + \mathbb{E}_{b_2|b_1} h_2(x_1, b_2) \tag{1}$$

$$\text{s.t.} \quad A_1 x_1 = B_1 x_0 + b_1 : \quad \pi_1 \tag{2}$$

$$x_1 \geq 0. \tag{3}$$

Where, for t=2,...,T we have the recourse function $h_t(x_{t-1}, b_t)$ defined as:

$$h_t(x_{t-1}, b_t) = \min_{x_t} \quad c_t\, x_t + \mathbb{E}_{b_{t+1}|b_t} h_{t+1}(x_t, b_{t+1}) \tag{4}$$

$$\text{s.t. } A_t x_t = B_t x_{t-1} + b_t : \qquad \pi_t \tag{5}$$

$$x_t \geq 0. \tag{6}$$

The decision variables of a particular stage t are represented by the decision vector x_t, which includes hydro generation, thermal generation, water storage at hydro power plant reservoirs and spilled water. The model's parameters vectors and matrices include: b_t represents deterministic electricity demand and a specific realization of the stochastic water inflows at stage t; c_t represents the operational cost vector associated with power generation and curtailment costs at stage t; A_t represents the model's structural constraint matrix at stage t that captures mass-balance, demand satisfaction, maximum hydro generation constraints and energy transfer constraints; $B_t x_{t-1}$ represents the storage in the system that is carried forward from stage $t-1$ and is available at stage t. Eqs. (1) and (4) represent the objective functions of the models at both the first and the t-th stage, respectively. The objective is to minimize present cost plus the expected value of the future cost. Equations (2) and (5) represent the model's structural constraints and their associated dual variables denoted π. Equations (3) and (6) are simple bounds on the decision variables. The term $\mathbb{E}_{b_{t+1}|b_t} h_{t+1}(x_t, b_{t+1})$ represents the expected cost function of stage $t+1$ given decisions x_t that were made in stage t, and the realization of the random parameter b_{t+1} (that affects the condition of the system at stage $t+1$).

The HTSP model implementation adopted in this work is currently in use by the ISO in Brazil for generation planning and scheduling studies [39,40]. This HTSP model uses an aggregate representation of the hydro power plants following a methodology similar to the one presented in [41]. Detailed formulations of the HTSP model can be found in [42] and [43]. The optimization algorithm used to solve such a problem is named stochastic dual dynamic programming [23] from the class of sampling-based decomposition algorithms [26,44–46]. Initial results of a HTSP model simulation are provided in the form of an operating policy, which indicates decisions to be taken once the uncertainty is reveled [26]. This operating policy is then tested using out-of-sample synthetic series (representing the future water inflows) and results of this process provides the necessary information to compute the system assured energy as described in [18]. Section 4.2 presents more details about the HTSP simulation process to compute the system assured energy.

4.2. HTSP simulation process to compute the system assured energy

The goal is to search for possible variations in the system assured energy given distinctive possibilities for future water inflows derived from climate scenarios simulated by the Eta climate model. In order to compute the system assured energy, the methodology defined in [18] was followed. In general terms, the system assured energy is computed after performing simulations with the HTSP model considering electricity demand aggregated in different regions of the power system. These simulations consider a 20-year planning horizon with monthly time steps. The first 10-year period is used for handling hydro reservoirs starting conditions. The last 5-year period is represented to set hydro reservoirs closure conditions. The system assured energy is established for the other 5-year period of the planning horizon, and for the intent of this paper, we call this period the “simulation period”. Initially, for the simulation period, the HTSP is represented in a scenario tree [37,39], and the goal is to obtain an operating policy.

Once the operating policy is available, the HTSP model considers 2000 synthetic series [39], generated to represent the random inflows at each time stage of the simulation period, to assess this policy and to obtain decision variable optimal values associated with each synthetic series. These decision variables values are then used to define the system assured energy as described in [18]. It is possible to obtain, for each month of the simulation period and at each synthetic series, the hydro generation targets aggregated by region, the thermal generation dispatches at each individual thermal plant and the operational marginal costs at each region. During this process, we consider a convergence criterion for demand supply risk of 5%, on average, with a tolerance of ±0.1%, i.e. for the 2000 synthetic series the power generation system has to supply the total demand in 1900 ± 2 synthetic series, at every time stage of the simulation period. If the demand supply risk is not achieved, it is necessary to adjust the system electricity demand and perform a new run of the HTSP model. This process is repeated until the desired stopping criterion is reached to obtain the total electricity demand that can be supplied by the power generation system during the simulation period. This total demand is equal to the system assured energy, and is used in Section 5 to identify impacts of climate change on Brazilian hydropower.

4.3. Assumptions regarding to simulation periods

The current way to assess the system assured energy uses the historical natural inflows with a time span of at least 30 years. This study is carried out using the simulation of these series for the future as explained in previous sections. The purpose of these new water inflow series is to represent future possibilities for the different scenarios of climate change. Different 30-year periods of natural water inflow data series were considered to perform the computations of the system assured energy at different moments in time. These 30-year periods of projected data for water inflows feed the HTSP model. They also serve as a basis for the construction of future scenarios of natural energy inflows for each subsystem (water inflows transformed into energy [40,43]) at each time stage of the HTSP using the periodic autoregressive model of order n (PAR-n) [25,39].

The first 30-year period starts in the year 1961 and is used to evaluate the system assured energy at year 1990. The data for this period is similar to the historical data obtained from direct measurements and interpolation for the same period. This first 30-year period is used to calibrate the climate and the hydrological models. The other three 30-year simulation periods start at years 2011, 2041, and 2071 and they are used to evaluate the system assured energy at years 2040, 2070 and 2100 respectively.

5. Simulation and results

5.1. Simulations structure

Fig. 6 shows a diagram that identifies all the simulations performed in this work. A total of 52 system assured energy simulations are used for evaluating the impacts from other uses of water, 30-year simulation periods and climate information. There are two power generation systems (EGS and FGS), four scenarios to represent other uses of water from Section 3.3 (country's economy in recession - RE, country's economy in a process of stagnation - PS, development of country's economy in a moderate proportion - DM, and country in a state of full social development - FD, considered only when analyzing the FGS), four 30-year periods (except when analyzing other uses of water that only consider the future periods), climate model Eta represented with two different resolutions,

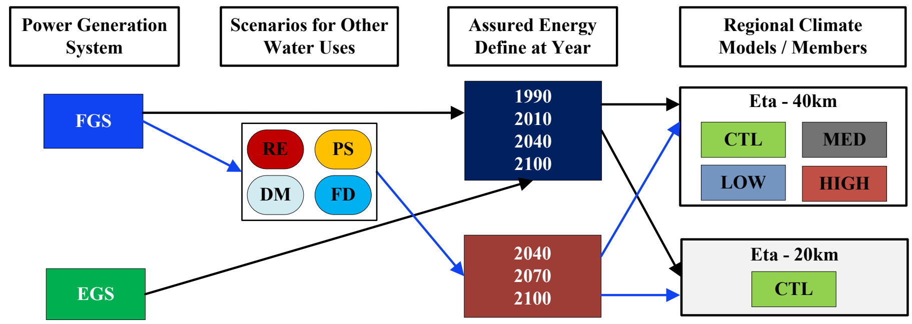

Fig. 6. Structure of system assured energy simulation cases.

40 km (with members, CTL, LOW, MID, HIGH) and 20 km (with member CTL).

For each one of the 52 simulation cases, it is necessary to run the HTSP model in average 20 times in order to achieve the adopted stopping criteria. One run of the HTSP model for the instance's size we consider requires about three days of simulation on a regular computer. In order to overcome this computational burden, a multi-threading version of the HTSP model was used in a distributed cluster with 30 machines (3.8 GHz Core i7 with 6 cores each) with 32 GB DDR3 1600. All these simulations required about 3 months of computational time at full load.

5.2. System assured energy results

We will refer to the system assured energy in terms of average megawatts (for simplicity we represent units with [MW]), which are commonly used to describe energy production over a specific period of time. In this analysis, we can think in terms of average megawatts produced over a month, which is the time stage discretization of the HTSP. For example, if we want to compute the total energy in MWh given the month average megawatts it is necessary to multiply such value by the number of hours in that month. Results for each EGS simulation scenario considering different climate information and not including variations on water use are presented in Fig. 7 and Table 1. The system assured energy is bigger for the first period (1990) considering all the four members of the Eta model. This is a concern for a country that relies basically on hydro resources displaying the existing plants together will produce less electricity in the future. The comparison between Eta-20 CTL and Eta-40 CTL shows that for this study the granularity level is not significant (see Fig. 8).

The results for the FGS show the same decrease in electricity

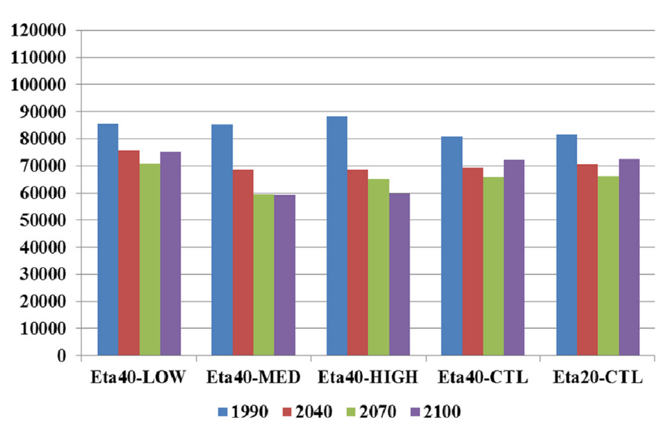

Fig. 7. EGS assured energy [MW] for each climate scenario.

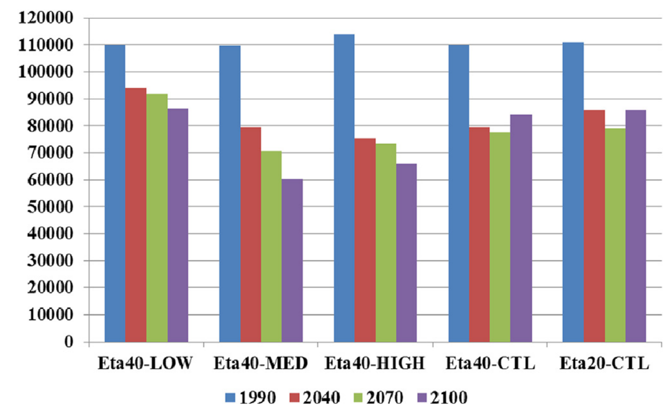

Fig. 8. FGS assured energy [MW] for each climate scenario.

generation, which means that with the planned new hydro power plants the effect of climate change will take the total generation to about 28% less than the planned power production. The drop in the system assured energy is more significant than the results obtained for EGS. Table 2 presents a relative comparison of FGS system assured energy with respect to the one obtained for the year 1990 for each power generation system. From Fig. 9, it is possible to notice the reduction of approximately 15% for EGS and 28% for FGS starting at year 2040. This reduction is observed with respect to simulations of the HTSP model for EGS and FGS and for Eta-40 CTL. However, similar patterns are obtained for the other members. This difference was expected from the hydrological results obtained and presented in different maps in Section 3.2 in which larger reduction in terms of rainfall would occur in the Northern region. The FGS reflects the new investments in hydro power plants in that region which causes the larger relative reduction of the system assured energy.

The influence of other water use projections also has a significant impact in the system assured energy. In general terms, increments in water demand reduce the availability of water to produce electricity at the hydro power plants. This is aggravated in scenarios of full development of the economy as shown in Fig. 10.

5.3. Sources of uncertainties and remarks

The analysis carried out in this work is based on several assumptions, data sources, modeling choices and regulatory rules. In this context, potential uncertainty in our results and interpretations are to be expected. Meanwhile, a broad uncertainty analysis was out of the scope of this particular study, therefore, it is important to mention the main concerns. The first point of concern is related to the climate variable information produced by the climate models

Table 1
EGS and FGS assured energy for each simulation case representing different climate information.

Eta Model case	EGS assured energy [MW]				FGS assured energy [MW]			
	1990	2040	2070	2100	1990	2040	2070	2100
Eta40-LOW	85,698	75,764	70,878	75,355	110,047	93,818	91,681	86,296
Eta40-MED	85,276	68,601	59,547	59,105	109,781	79,310	70,827	60,310
Eta40-HIGH	88,409	68,615	65,249	59,656	113,809	75,383	73,565	65,959
Eta40-CTL	81,048	69,250	65,913	72,231	109,915	79,328	77,426	84,012
Eta20	81,764	70,500	66,375	72,599	110,691	86,099	78,969	86,087

Table 2
System assured energy variation in [%] – EGS X FGS.

Eta Model case	Existent generation system			Future generation system		
	1990–2040	1990–2070	1990–2100	1990–2040	1990–2070	1990–2100
Eta40-LOW	−11.6	−17.3	−12.1	−14.8	−16.7	−21.6
Eta40-MID	−19.6	−30.7	−30.7	−27.8	−35.5	−45.1
Eta40-HIGH	−22.4	−26.2	−32.5	−33.8	−35.4	−42.0
Eta40-CTL	−14.6	−18.7	−10.9	−27.8	−29.6	−23.6
Eta20	−13.8	−18.8	−11.2	−22.2	−28.7	−22.2

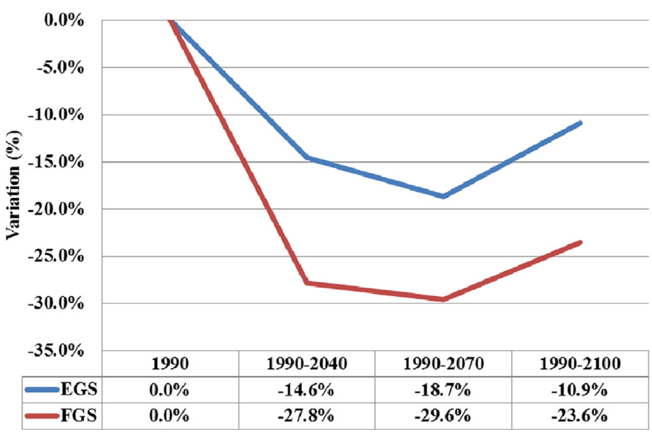

Fig. 9. EGS X FGS: Assured energy variation from Eta-40 CTL simulation cases.

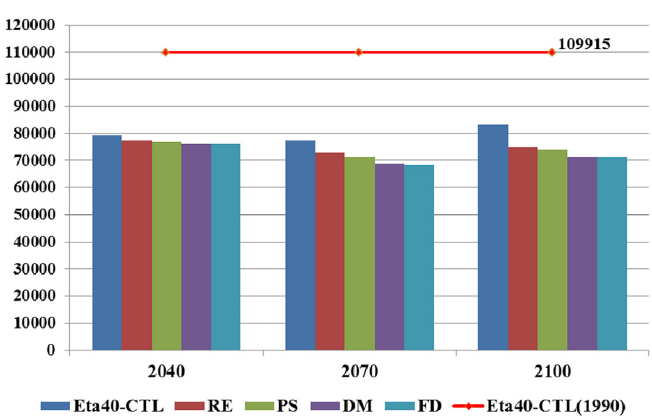

Fig. 10. FGS assured energy [MW] considering other water uses and Eta40-CTL.

required in the analysis. In this study, a number of water inflow time series at each hydro power plant has been derived from artificial weather observations from the GCM HadCM3 downscaled with Eta regional models. Meanwhile, the GCM HadCM3 and the Eta regional model were chosen due to their satisfactory performance to represent the climate in South America. Certainly, such information presents limitations for specific areas or climate events where climatic processes are not well represented.

Information from other climate models can be used in future studies to carry out related analysis. In terms of climate change scenarios, the A1B scenario was investigated from IPCC, which represents an emission pathway with average growth of future CO_2 emissions. Different increases in global temperature affecting the CO_2 concentration in the atmosphere for the A1B scenario were also used in our analysis. Other scenarios, representing more conservative, or more optimistic CO_2 emission pathways, can be used to compare results in future work. We also have a potential source of uncertainty related to other water uses for a subset of simulations. Thus, we evaluate four different scenarios for other water uses ranging from a scenario representing the country's economy in recession to a scenario with full development of the country's economy. In this given context, it is possible to notice that the negative impacts in hydropower are intensified in every scenario, but they are not of the same magnitude posed by climate information.

Another potential source of uncertainty lies in the configuration of the power generation system (EGS and FGS). It was possible to notice more significant reductions in system assured energy for the FGS. However, it is likely that the FGS configuration in the future may not be the same as the one represented here, therefore, neither would the system assured energy. In terms of the HTSP modeling and the system assured energy evaluation procedure, improved schemes may be designed and rules may be changed in the future. This is related to regulatory uncertainties, which also can affect the results of the analysis. Further works should explore how such improved schemes could influence the results, but the main conclusions of this work are not expected to drastically change. For instance, an assumption made along this study was to consider an aggregate representation of hydro power plants inside each electric subsystem (Sections 2 and 4.1) following the current HTSP modeling approach adopted in Brazil.

6. Conclusion

In this work we provided a framework and carried out an analysis using a combination of climate projections downscaled at regional levels, a rainfall-runoff model and a power generation scheduling optimizer to investigate the possible effects induced by climate change in the energy production of a hydro-dominant power system. The evaluation of future effects of climate change in power generation has gained more attention due to an increase in the investment in renewable power plants. This work presents an analysis of the effects of climate change in the Brazilian power system, where the majority of electricity production comes from hydro sources. The assessment of climate projections on the system assured energy, which is the metric adopted in Brazil for the power generation system, is crucial because it guides the future investments and consequently the composition of the country's future electricity generation portfolio.

In recent years, the Brazilian government through national plans has essentially set the electricity generation capacity expansion to hydro power projects in the Amazonian region. Because of environmental constraints and natural characteristics of the region the majority of these projects are based on run-of-river technologies, which make them highly susceptible to changes in water inflow patterns. The sole use of water inflows historical data for such projects, not including the dynamics associated with climate changes, will likely produce decisions that can derive great regrets in the future. For example, this paper shows that the assured energy will be lower in percentage terms (directly affecting these projects cash flows) when the climate information is considered in the FGS, especially because the average precipitations are projected to decrease and the drown periods are likely to increase in the Amazonian region. Although some safeguards need to be incorporated regarding simulation models, regulatory issues and other things, the paper has shown the importance of considering climate projections when evaluating investments in future hydro plants. This paper brings valuable insights into this matter which not only pertain to hydropower generation, but also can be further extended to other primary sources such as wind, biomass and solar.

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