

The Influence of Climate Change on Hydro Generation in Brazil

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Abstract—More than 85% of the total electricity generation in Brazil comes from Hydro Plants. The hydroelectricity is a good example of renewable resources which, in this case, depends greatly on the precipitation. An optimization program is used in order to determine the dispatches of the plants and to minimize the operational costs. Given a set of hydro plants it is possible to calculate the power system assured energy or the amount of energy available to supply the load at a deficit risk of 5%. However, climate change can cause great variation on the assured energy. The problem drastically aggravates for the new available hydro potentials located in the Amazon region which probably will be affected by the global warming. This paper provides the initial results of a research project sponsored by generation companies and the regulatory agency in Brazil.

Index Terms — Climate Change, Economic Dispatch Optimization, Hydrothermal coordination, Renewable energy.

I. INTRODUCTION

Renewable energy has been the main topic around the world as a solution or a partial solution to replace the current fossil fuels generation that contributes to the global warming threat. The burning of fossil fuels causes an increase in CO₂ emissions which are the main component of the greenhouse effect. Hydro energy is one example of renewable energy like others such as wind, solar and biomass. All of these renewable sources depend on the weather conditions and climate forecast, i.e., the “fuel sources” are not controllable. For the wind and solar this is very true but for the hydro and biomass there is some possibility of storage in special conditions. For instance, in the case of hydro plants, large reservoirs can store water for the dry periods. Usually, it is necessary to flood a great amount of land in order to construct large reservoirs. This is a delicate problem, where environmentalists are fighting against the construction of large reservoirs by trying to persuade governments with their opinion. Nowadays, this is the Brazilian particular case where new entrepreneurs are becoming run-of-river plants which are highly dependable on precipitation.

This paper provides the initial results of a project under development in Brazil about the effects of climate change on

the annual variation of the precipitation average and on its seasonality. Given that the regime of rain in some basins may change, the results of this work are vital for the generation plan in terms of the energy matrix and of the placement of new power plants.

Section II presents the structure of the research project describing the main goals of each different research area involved in this work. Section III presents the methodology to evaluate the assured energy. Section IV presents some test results of the methodology. Section V concludes and points out for future research directions.

II. STRUCTURE OF THE PROJECT

The project was structured in three main parts from the climate prediction to the energy calculation. The hydrology is in the middle to identify the water trajectory. The consumption of water depends on the use of the soil and the water consumption in urban areas. The main parts of the project are presented in Figure 1.

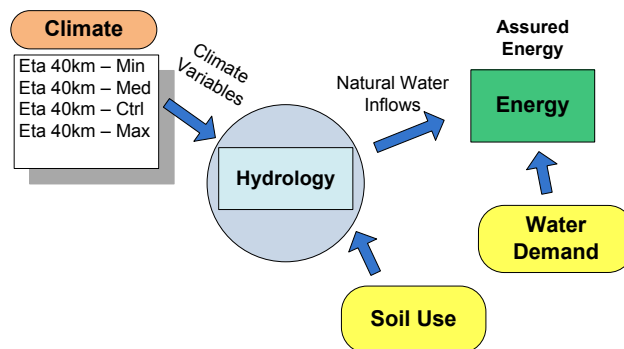


Figure 1. Main parts of the project

A. Climate

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) with the purpose to study the current

scientific knowledge in climate change and evaluate its potential environmental and socio-economic impacts. Since then, the IPCC assessments became an important tool to guide the implementation of policies in response to climate change. The Fourth Assessment Report (AR4), which was released in 2007 under the title “Climate Change 2007”, confirms that climate change is already a reality, and illustrates the impacts of global warming occurring nowadays and in future. At this project, amongst the several scenarios for greenhouse gas (GHG) emissions from 2000 to 2100 to forecast the global surface warming, the A1B scenario (stabilization scenario with balance between energy sources) has been chosen because it represents the average for the CO₂ emission scenarios, i.e., not so high and not so low. [1].

Four members of HadCM3 global model given by the UK Met Office Hadley Centre - United Kingdom were constructed on variations of the emissions scenario A1B, named high, medium, control and low. The mathematical models of the Global Climate System are the best tool to generate likely future climate change scenarios, as they allow the simulation of likely climate change scenarios for different CO₂ emission scenarios. In order to observe the impact of the climate change at the hydro basins, more detailed information is necessary. Thus, the development of dynamic downscaling techniques using Regional Climate Models (RCM) that gives greater spatial and time details of the climate system variables than the Global Climate Models (GCM) became essential to study the climate change in regional scale [2]. The Eta-CPTec regional model with 40 km resolution over South America for the present climate (period of 1961 to 1990) and future climate (three periods 2010 to 2040, 2041-70, 2071-2100) is applied in this project [3], [4]. This model contains CO₂ variation, vegetation seasonal variation, 360 calendar days synchronized with HadCM3 global model calendar. These four members of Eta simulation are then used to generate the precipitation data which is the main input variable of the hydrologic model.

B. Hidrology

At this part the climate change impacts on water flows are simulated along with trend analysis of the water flow series and changes on soil use. The MGB-IPH model [5] is used for performing this calculation. In order to fulfill this objective the model builds a function for each basin that relates of the precipitation with the water inflows and the identification of vegetation influence on the inflows. This model is based on the LARSIM model [6] and VIC model [7], [8] with some adaptations. The original soil water balance of LARSIM model was simplified and the vaporization was included [9]. The model is distributed over the space, which means that the hydro basin is split in small units. In the original version of the model the basins were divided into square cells with sides of 10 km. In the current version the basins are divided into geomorphologic parts, named mini-basins, which are interconnected by a drainage network. The model is composed by the following algorithms: soil water balance; evaporation; superficial, sub-superficial and subterranean drainage. Each mini-basin is decomposed into blocks or response hydro units (RHU) which are clustered to form the grouped response units (GRU) [10]. Each GRU is characterized by a set of parameters like the maximum water storage at the soil, the vegetation

foliar area and so on. The hydro balance is computed for each RHU and the inflows of each RHU are added and propagated to the drainage network. The leakage of each soil level does not instantly reach the drainage network, but has some delay in the interior of the mini-basin [11]. The leakage model uses the length, slope, roughness and the average width of the river parts [12]. The precipitation, temperature, relative humidity, insulation, wind speed and atmospheric pressure in one cell are computed based on interpolation of the nearby available data.

Another important step is the calibration of hydro parameters which needs to take into account the physical characteristics and the historical data of similar basins. Besides the manual procedure based on the sensibility of the analysts an automated procedure is also performed [13]. In this work, the MGB-IPH model was calibrated using recent data (from 1960 up to now).

The set of hydro generation stations chosed to compose the power generation system is the one established by the Brazilian government for the 2025 horizon [14]. Figure 2 shows the main basins and the existent hydro generation stations.



Figure 2. The River Basins and the Hydro Generation Stations
Source: Brazilian National Water Agency - ANA

Behavior changes, such as precipitation increase or decrease, as well as medium flows increase or decrease were identified. Precipitation data were compared to the future climate projections in order to verify if the trends observed are consistent with the projections made.

The impact of water demand for agriculture that may compete with water use for hydro electricity generation must be added to the hydrological model. Moreover, the consumption of urban areas needs to be forecasted based on economic projections to complete the model. In this initial phase, these variables were not included in the model.

C. Energy Computation

The objective of this part is to estimate the assured energy that generation power plants can produce in the system.

Assured energy is the hydro plant's physical assurance, which constitutes the maximum amount that a hydro plant can use for trading purposes [15]. For the assured energy estimation, the water inflow series, output from the hydrological model, plays a very important role, especially in a hydro-dominated power system like Brazil. These series are a key point to evaluate changes in the river basins and further in the hydro energy availability of the Brazilian national interconnected power system.

The water inflows generated by the Hydrology group are used as input for an optimization model that attempts to solve the hydro-thermal scheduling problem (HTSP) in Brazil. A multi-stage stochastic optimization version hydro-thermal scheduling problem is implemented in the NEWAVE software in Brazil. NEWAVE is used to determine the electrical system operational strategy that minimizes the total operation cost (present + future). In the scope of this work, NEWAVE is used to determine the total available generation for an energy deficit risk of 5% and consequently the system's "assured energy". Section III describes with more detail the HTSP and the simulation process to obtain the assured energy of the interconnected system.

III. HYDRO-THERMAL SCHEDULING AND ASSURED ENERGY EVALUATION

In a HTSP one is interested in minimizing the production costs of electricity to supply the system demand considering the operation of both hydro and thermal plants. In the electricity power system, the independent system operator (ISO) may decide to use the water available at the hydro plant reservoirs to produce electricity. Doing so avoids the economic expense required to dispatch thermal power plants, but can risk hydro availability in future time periods. The water available to produce electricity is bounded by the reservoir storage capacities and future water inflows at the river basins of these reservoirs. Most of the time thermal generation must be used to complement the necessary amount of electricity to meet system demand. However, wise use of the hydro and thermal system resources can reduce costs.

The available hydro generation capacity at a particular time period depends on the amount of water stored in the hydro generator's reservoir. If this hydro generator is part of a cascade system (there are generators upstream and/or natural water inflows are responsible for a large part of the future water supply that will be available to generate electricity. These future water inflows and their stochastic nature complicate the resulting hydro-thermal scheduling model. The problem is dynamic because present decisions affect the future, what couples the problem in time.

In the HTSP, there are multiple interconnected hydro reservoirs in the system that need to be scheduled over many time periods. This combination with stochastic inflows means that the problem can be defined as a multistage stochastic program. The objective is to determine the optimal amount of hydro and thermal electricity to be produced at each time period satisfying the problem constraints such that expected operating costs of the system are minimized.

A. HTSP in Brazil

For the purpose of assured energy evaluation, we are interested in solving the HTSP for long term horizon, that we call from now on HTSPL. The horizon defined for the HTSPL is 20 years with monthly discretization. In Brazil, the HTSPL is modeled in NEWAVE considering an aggregate reservoir representation (ARR) [16-17] of the hydro plants in order to reduce the size of the model.

The ARR, also known as the equivalent reservoir representation, was first mentioned by Pierre Mass in the mid 1940s. In [16] it is presented the first ARR model with application to the multi-reservoir hydroelectric power system in the Pacific Northwest. The ARR is an aggregation technique used to reduce the size of the model by aggregating multiple reservoirs inside a specific region to a single aggregate reservoir. The use of ARR consequently reduces the computational effort required to solve a hydro-thermal scheduling model. This type of representation models total hydro generation of a power system or even a specific region inside the system. The main idea of this approach is to deal with everything in terms of energy instead of water.

The main goal in formulating a model of the HTSPL with an aggregate reservoir representation (ARR) is the same as that with individual hydro plants, minimize present and future operational costs subject to a set of constraints. The main difference is that in a model with the ARR, we deal with energy instead of water. Random water inflows and water reservoir volumes are transformed into energy for an aggregate reservoir using the hydro generator productivities along the cascade. Now instead of a solution yielding individual targets for the hydro generators, a solution yields generation targets for the each aggregate reservoir during the planning horizon.

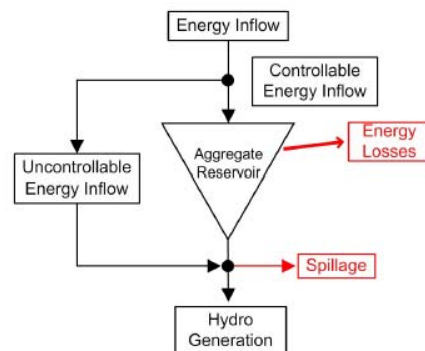


Figure 3. Aggregate Reservoir Representation

The hydro plants inside a region are aggregated into a single reservoir that has both controllable and uncontrollable energy that can be used to produce electricity. The periodic autoregressive (PAR) model is used to generate future energy inflow scenarios for the ARR [18]. The energy inflows are divided into controllable and uncontrollable inflows. Both the controllable and the uncontrollable inflows may be used to generate electricity immediately but only the controllable inflows can be stored for future use. The ARR considers energy losses at the aggregate reservoir due to evaporation, diversion of water (e.g., for agricultural use) and water

spillage. Figure 3 depicts some of the parameters of an aggregate reservoir.

The following mathematical model presents a general representation of the HTSPL as a T-stage stochastic linear programming with recourse currently implemented in NEWAVE.

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

$$\text{s. t. } A_1 x_1 = B_1 x_0 + b_1; \quad \pi_1 \quad (2)$$

$$x_1 \geq 0 \quad (3)$$

where for $t = 2, \dots, T$,

$$h_t(x_{t-1}, b_t) = \min_{x_t, \theta_t} c_t x_t + \mathbb{E}_{b_2|b_1} h_2(x_1, b_2) \quad (4)$$

$$\text{s. t. } A_t x_t = B_t x_{t-1} + b_t; \quad \pi_t \quad (5)$$

$$x_t \geq 0 \quad (6)$$

The decision variables of a particular stage t are represented by the vector x_t that includes hydro generation, thermal generation, energy storage at the ARR, spilled energy. The parameter b_t represents a specific realization of the stochastic energy inflows at stage t . A detailed formulation of the problem can be found in [17]. Equations (1) and (4) represents the objective functions of problems at stage 1 and t respectively. The objective is to minimize present cost plus the expected value of the future cost. Equations (2) and (5) represent the models structural constraints that basically include energy balance and demand satisfaction constraints. Associated with the structural constraints we have dual variables π . The dual variables associated with the demand satisfaction constraints are considered to be the operational marginal costs (OMC) basis of the electricity spot prices in Brazil. Equations (3) and (6) are simple bounds on the decision variables.

NEWAVE solves the general HTSPL using the stochastic dual dynamic programming algorithm developed Pereira and Pinto and presented in [19]. At the end of the SDDP convergence process, NEWAVE identifies a policy that specifies what decisions to take with the ARR variables and thermal plants dispatches at each time stage for a set of energy inflow series. Also, NEWAVE gives information about the OMCs for each inflow series simulated. This information is used in the evaluation of the assured energy.

B. Assured Energy Evaluation

The assured energy of each hydro plant is understood to be the fraction of the power generation system's global assured energy. The term assured energy can also be used to define the maximum amount that a power generator can negotiate in the market. We are interested in this work to analyze not the assured energy of each power plant but the aggregated amount of hydro and thermal plants of the entire system. The idea is to identify possible variations in the total assured energy of the system given the different possibilities of the future inflows derived from climate change.

In 2004, the Brazilian Minister of Mines and Energy established the methodology to compute the assured energy [20]. The assured energy is computed through static

simulations of the power generation system with the NEWAVE program using four electricity submarkets named: Southeast – SE, South – S, Northeast - NE and North – N. NEWAVE determines for each month of the planning horizon the hydro generation of each submarket, the thermal generation of each plant and the operational marginal costs.

All the simulations performed with NEWAVE used to evaluate assured energy consider a 20-year planning horizon with monthly discretization. The first 10-year period is represented to stabilize initial conditions of the ARRs. The last 5-year period is represented to set the ending conditions of the ARRs. From year 11 to 15 the assured energy is established, for the purpose of this work we call this simulation period. It is necessary to adjust the risk supply criteria that is pre-established to be 5% in average for the simulation period. For the simulation period NEWAVE uses 2000 synthetic series of energy inflows and we use the decision variables information from these series to define the assured energy. If the risk supply criterion is above or below 5% in more than 0.1% it is necessary to adjust submarket loads and to run NEWAVE again to get new results. This process continues until we reach the desired stopping criteria.

The flowchart of the process to obtain the assured energy is presented in Figure 4.

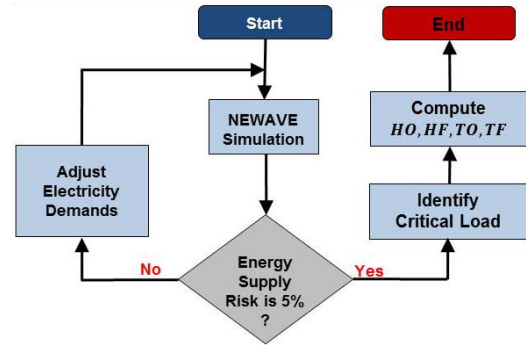


Figure 4. Assured Energy Computation Flowchart

Once the risk supply criterion is reached we have the information about how much electricity demand the power generation system can supply during the simulation period given the acceptable tolerance. The supplied electricity demand of system is called critical load. A fraction of the critical load is supplied by hydro generators (hydro generation offer) and the other fraction is supplied by thermal generators (thermal generation offer). In order to determine those fractions the current methodology uses the operational marginal costs (OMCs) for each synthetic energy inflow series. The hydro generation offer is then defined in (7).

$$HO = \sum_{i \in I} CL_i \cdot HF \quad (7)$$

where, CL_i represents the critical load obtained for an assured energy offer of 95% for submarket i . HF represents the hydro factor computer using (8).

$$HF = \frac{\sum_{i \in I} \sum_{j \in J} \sum_{s \in S} \sum_{m \in M} gh_{ijsm} \cdot OMC_{ijsm}}{\sum_{i \in I} \sum_{j \in J} \sum_{s \in S} \sum_{m \in M} [gh_{ijsm} + \sum_{n \in N} gt_{ijsm}^n] \cdot OMC_{ijsm}} \quad (8)$$

where, I represents the set of submarkets, J represents the set of years (11 to 15), S represents the set of energy inflow series (2000), M represents the set of months of a year and N represents the number of thermal plants in the system. The variable gh_{ijsk} represents the total hydro generation for each ARR, gt_{ijsm}^n represents the thermal generation for each thermal plant, and OMC_{ijsm} represents the operational marginal cost of each submarket.

The thermal generation offer is defined by (9)

$$TO = \sum_{i \in I} CL_i \cdot TF \quad (9)$$

where, TF represents the thermal factor computed using (10).

$$TF = \frac{\sum_{i \in I} \sum_{j \in J} \sum_{s \in S} \sum_{m \in M} OMC_{ijsm} \cdot [\sum_{n \in N} gt_{ijsm}^n]}{\sum_{i \in I} \sum_{j \in J} \sum_{s \in S} \sum_{m \in M} [gh_{ijsk} + \sum_{n \in N} gt_{ijsm}^n] \cdot OMC_{ijsm}} \quad (10)$$

The sum of HO and TO gives the total assured energy of the system. It is important to mention that the assured energy can be defined for each individual power plant. It is current practice in Brazil to determine the assured energy of the system and then define each individual amount sharing the total in a specific way. But this is not the purpose of this work, our interest lies in the definition of the assured energy for the whole system using the natural inflows series generated for the future that are influenced by climate variables.

IV. CASE STUDY

The chain of tasks is tested with water inflow series generated using climate variables for two periods 1961-1990 and 2011-2040. The power generation system with the existent power plants and the addition of the new power plants proposed by [14] is used. This initial phase of the project is important to validate the innumerable models and the large amount of data which are applied in the calculation of the assured energy.

For the climate part, the 1961-1990 period was chosen to adjust the model with the actual historical data. The controlled member of HadCM3 associated with the Eta downscaling for the South America is used to generate the precipitation series either for 1961-1990 and 2011-2040 periods. With the climate variables including precipitation, temperature and wind speed, the future water inflows are calculated using the model MGB-IPH, for the same time periods (1961-1990 and 2011-2040).

Static simulations using NEWAVE with the hydro-thermal configuration of the Brazilian national interconnected power system are performed. We considered four interconnected submarkets (Southeast/Center West, South, Northeast and North). A 20 year horizon is considered for NEWAVE simulations and our interest lies on years 11 to 15. As mentioned before, the average risk of the simulation period is used to calibrate the supply criteria compliance. After the SDDP convergence is achieved, NEWAVE policy simulation considers 2000 energy inflow synthetic series statistically generated with the periodic autoregressive (PAR) model using the hydrological series coming from the MGB-IPH model for the two considered periods. A simple adjustment procedure for the electricity demand is assumed in order to reach the risk

average stopping criterion. Figure 5 provides the main results for the case study.

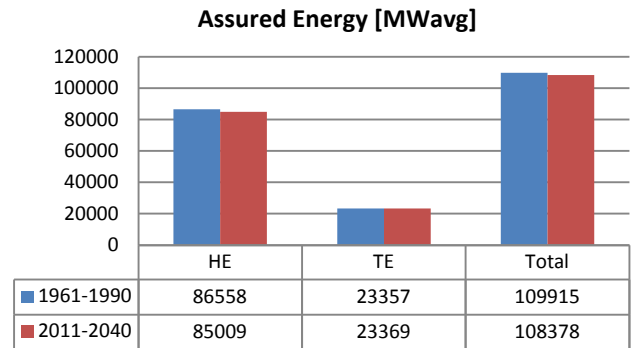


Figure 5. Assured Energy Results

It is possible to notice from Figure 5 that for the two cases analyzed the period of 2011-2040 that corresponds to the future presents a reduction of approximately 1500 [MWavg] with respect to the period of 1961-1990. These results were obtained with the control member of the Eta model with 40 km resolution to generate the climate variables and the MGB model to generate the water inflow series for the two periods considered in NEWAVE simulations.

It is important to stress that these initial results come from a test case and are still under a validation process. Given that the preliminary results are correct, the total energy generated by the generation system proposed by [14] is less than the energy calculated using the historical hydro series. If the climate scenario is corrected, there would be a deficit of energy in 2040 for the planned generation system.

V. CONCLUSION

The assessment of the effect of climate change on the amount of available hydro generation is a crucial problem for many countries in the world including Brazil. The Brazilian Minister of Mines and Energy is basically setting the generation expansion at the rivers located in the Amazon region. This paper shows the methodology that is applied to compute the variation on the future available hydro energy generation considering not only the amount of inflows that reach each reservoir but also the hydro series seasonality. The goal of the next part of this project will evaluate the changes in the assured energy for different members of the ETA model and also for different climate global models. In the same way, the results of the climate variables output from these models will be used to generate new water inflow series in order to perform new energy simulations with NEWAVE.

Due to environmental constraints, the new hydro plants that will enter in the Brazilian power system in the future are basically run-of-river plants. Changes on hydro series pattern are very important and it directly affects the energy generation of hydro plants, especially for run-of-river plants. These changes in patterns should be considered during the construction of the generation plan.

The PAR model generates the synthetic inflow series for NEWAVE assumes that stationary time series. A future research goal is to account for non-stationary effects from climate change on water inflow series by replacing the PAR model with, for instance, a dynamic linear model [21].

The proposed approach can be applied for most of the renewable sources including wind and solar generation.

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