Technical Session 3B (11:10 - 12:40)	**Scenario Generation and Uncertainty Models**	**Chair: Débora Jardim, ONS**	
	Multidimensional Quantile Regression Model for the Long-Term Hydrothermal Scheduling Problem	Felipe Beltrán	NORUS
	A New Approach to Adjust Autoregressive Models for Generating Synthetic Water Inflow Series Based on Metaheuristics.	Edimar Oliveira	UFJF
	Effects of Systematic Bias in Inflow Forecasting on the Operational Planning of the Brazilian Energy System	Alexandre Street	PUC-RJ
	Handling the Impact of Climate Change in the Long-Term Generation Scheduling Problem via Distributionally Robust SDDP	Renata Pedrini	UFSC

Multidimensional Quantile Regression Model for the Long-Term Hydrothermal Scheduling Problem

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The Long-Term Hydrothermal Scheduling (LTHS) plays an important role in the coordination of the use of water under future uncertainties in predominantly hydroelectric electrical systems. Operation policies are the result of the LTHS problem and the guide for future operation in the medium and/or short-term scheduling programs. The methodological alignment between both programs is a key property for time consistency in the stochastic programing framework.

The current Brazilian framework computes a LTHS policy monthly and executes a medium-term program weekly with forecast updates. The lag between the time the policy was computed and consulted is a potential source of time-inconsistency of the future seen by the medium-term program and can result in abrupt changes in energy allocation, increasing volatility in price formation throughout the weeks.

Besides the lag between the LTHS updates, methodologically, the time-inconsistence occurs because an autoregressive coefficient of the long-term inflow scenario generation process is present in the policy formulation. This work focuses on two aspects of this condition: (i) reducing the sensibility of the autoregressive component of the LTHS policy and (ii) improving the quality of the policy computation with a less biased sample space in the LTHS problem.

This work proposes a novel approach for the Quantile Regression (QR) model in the Stochastic Dual Dynamic Programming (SDDP) framework. Strategies for multidimensional sample space representation and strictly positive realizations of the random variables were developed. In our approach, the QR model is applied in the Backward pass of the SDDP method.

The advantages of using the QR approach with SDDP are:

- A suitable sample space representation of the stochastic process with time dependence between consecutive stages.
- Computational gain in LTHS convergence due to the reduced state space compared with an autoregressive model of order greater than one.
- Avoiding negative realizations of inflows in the Backward pass.
- The use of any model that is considered the best fit for scenario generation in the Forward pass.

The disadvantages are:

- The need for a different model in the Forward pass since the QR model does not perform well for scenario generation.
- Different formulations in SDDP.
- Risk-aversion recalibration.

The proposed QR model was implemented for a simplified representation of the Brazilian interconnected system, which comprises 141 individually modeled hydro plants. Its performance was extensive compared with a linear Periodic Autoregressive (PAR) model, which was applied in the Forward pass as well as in the out-of-sample scenario generation of both policies. The policies were computed for a 36-month planning horizon with 20 inflow realizations per month. The period between December 2018 and March 2019 was selected for benchmarking, a time of substantial volatilities in Brazil's energy price.

Out-of-sample simulation results demonstrated that policies computed with the QR model provided superior management of hydro resources compared with the PAR model. Specifically, reservoir levels were kept consistently higher under the QR-based policy, reducing exposure to critical water shortages. Despite the conservativeness of the reservoir management strategy, the QR model managed to keep thermal generation and, consequently, energy prices, at similar or even lower levels than the PAR-based approach. Additionally, total spillage remained comparable between the two models, indicating that the QR model efficiently allocated water resources without excess losses. Most importantly, the QR model effectively mitigated the volatility observed in energy prices during the benchmark period, demonstrating its potential to enhance price stability in hydrothermal markets. Beyond operational performance, the QR model also exhibited computational advantages. The lower bound stabilization in the SDDP algorithm was achieved with fewer iterations compared with the PAR model, suggesting potential improvements in convergence speed and overall computational efficiency. This characteristic could be particularly valuable for large-scale, high-resolution planning models that require frequent updates and recalibrations.

Overall, these findings indicate that the QR-based approach is not only competitive with the well-established PAR model but also offers potential benefits in terms of operational efficiency, energy price stability, and computational performance, improving the solution of the LTHS problem for large-scale hydrothermal systems. The QR model could be tested in the official models of the Brazilian electricity sector to verify such benefits in the schedule programming process and price formation.

A New Approach to Adjust Autoregressive Models for Generating Synthetic Water Inflow Series Based on Metaheuristics

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The efficient coordination and operation of power systems, as Brazilian Interconnected System, depend on optimal electro-energy planning. On the top of the planning chain, medium-term planning with a horizon of five or ten years ahead and monthly discretization represents the largest horizon, and its results serve as the basis for short-term planning and daily scheduling. In order to solve the optimization problem which ensures the optimal use of water and thermal units in medium-term planning, Stochastic Dual Dynamic Programming (SDDP) is currently used to define the best operational policy. Due to the largest horizon and consequently their intrinsic stochasticity, there is a need to represent water inflow scenarios or natural energy inflow through synthetic series [1].

As discussed in [2], in order to generate synthetic series, a Periodic Autoregressive PAR(p) model is adjusted using the partial autocorrelation function and through the successive solution of the Yule-Walker equations as defined by Box & Jenkins. Althoug PAR(p) models, calculated through Box & Jenkins, can be able to guarantee the representation of a great number of water inflow scenarios due to the seasonal correlation effect, autoregressive models calculated using this statistical methodology may exhibit high orders and, consequently, negative coefficients that lead to the creation of positives Benders cuts, making the convergence of SDDP more difficult. Besides that, PAR(p) models with negative coefficients has more probability to generate negative synthetic water inflow which is unreal [3].

In this sense, this work proposes a new methodology for adjusting autoregressive models through metaheuristics. To this end, a Mixed Integer Nonlinear Problem (MINLP) will be formulated, which will define the optimal order and positive coefficients of an autoregressive model so as to minimize the standard deviation of the error vector. It is known that MINLPs have a large number of local minima (whether good or not) and may exhibit a discontinuous solution region. Thus, the work uses two recent metaheuristics (Arithmetic Optimization Algorithm and Coati Algorithm) to adjust, through an intelligent iterative process, both the order and the optimal positive monthly coefficients of an autoregressive model. For comparison purposes, the monthly autoregressive models and their respective error vectors calculated by both metaheuristics will be compared to each other and with those adjusted via Box & Jenkins. Besides that, synthetic series will be generated by each autoregressive model ensuring a more detailed comparison. All simulations will be performed using water inflow data recorded in the NEWAVE deck, providing realistic applications for hydropower plants considered in medium-term planning.

The results show that the metaheuristics are able to adjust autoregressive models with exclusively positive coefficients and, consequently, lower orders compared to the statistical methodology of Box & Jenkins without losing the quality of error vector. Finally, the synthetic series generated by models computed using metaheuristics tend to have a lower frequency of negative scenarios. Therefore, the proposed methodology is applicable in the context of medium-term planning, offering solution quality.

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Effects of Systematic Bias in Inflow Forecasting on the Operational Planning of the Brazilian Energy System

Arthur Brigatto[*], Alexandre Street[†], and Joaquim Dias Garcia[‡]

From the intricate balance of short-term electricity dispatch to strategic long-term resource planning, models and their underlying data form the backbone of power system operations worldwide. Therefore, the effectiveness of these systems depends not only on sound policymaking and innovative market designs but also on the reliability of the data and forecasts that drive decision-making processes. In particular, systematic inaccuracies in forecasts–whether due to bias, imprecision, or misalignment with operational realities–can propagate through the chain of models used to dispatch, plan, and price electricity, jeopardizing system reliability and efficiency.

Hydropower is the primary renewable source for electricity generation within the Brazilian energy infrastructure, representing a significant portion of the installed capacity for power generation as of May 2023, totaling 59.3%. Even in cases of drought, hydroelectric plants still account for the majority of electricity generation in this country. In this context, a long-term multistage dispatch planning model, generally based on the Stochastic Dual Dynamic Programming technique (SDDP), is used to estimate the opportunity cost of water, which is then used in the short-term operation procedures to define the day-ahead scheduling and market prices. However, this multistage operational policy heavily relies on multiperiod forecasts (e.g., 60 months in Brazil) of water inflow time series. Hence, any systematic bias in the inflow forecasts can impact the water values and compromise the optimal usage of this scarce resource over time.

From the empirical side, serious droughts have been observed in Brazil since 2013, with the most recent one occurring in the second semester of 2021. However, the dispatch orders suggested by the official models often delayed the activation of preventive actions, such as thermoelectric dispatches in pre-crisis situations – even though it was clear that these actions were needed at that time. This recurrent pattern has systematically triggered out-of-merit emergency dispatch orders, leading to high costs that consumers end up paying. In 2021 alone, these costs reached more than R$19 billion. Interestingly, at the same time, observed inflows have been systematically falling short of forecasts in the last decade.

After the 2021 crises, the regulatory willingness to change the governance of models and data triggered a series of public calls for contributions, which led to the National Council for Energy Policy approving Resolution No. 1, dated March 12, 2024 (officially published on April 19, 2024). This resolution established new guidelines aiming to ensure the coherence and integration of input data, parameters, methodologies, and

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computational models utilized by the Ministry of Mines and Energy, the Energy Research Company (the planner), the National System Operator, and the Electric Energy Trading Chamber (the market operator).

From the academic side, reasonable evidence has been reported in the literature regarding the detrimental effects of optimistic bias in the water value assessment due to simplifications in operational models. This work extends these findings by investigating how an optimistic bias in inflow forecasts affects the operation planning of Brazil's energy system.

We first present statistical evidence of this optimistic bias by analyzing the official NIE forecasts for the Southeast and Northeast subsystems from 2011 to 2024. We report statistically significant biases (2.5% level) were observed, with bias levels ranging from 6% to 109%, depending on the forecast horizon.

We then link the reported optimistic bias in inflow forecasts to certain distortions observed in system operation, as previously described. To achieve this, we analyze reservoir storage levels, thermal generation, and spot prices. We provide empirical evidence from Brazilian power system data that corroborates this link.

Furthermore, we investigate these effects from a more systematic perspective. We conduct a controlled experiment to produce more robust evidence on the impact of inflow forecast bias on the reservoir levels, thermal generation, and spot prices. For this purpose, we simulate the operation of the Brazilian system using the official PARp-A methodology and use it as the control to contrast it with the operation under an unbiased forecast.

Our findings bring relevant and robust evidence of the significance and impact of inflow forecast bias on the Brazilian power system operation, water management, and market results. The results also offer regulatory insights into models and data governance, which could help improve dispatch and market efficiency in this context.

Handling the Impact of Climate Change in the Long-Term Generation Scheduling Problem via Distributionally Robust SDDP

Renata Pedrini, Felipe Beltrán, Güzin Bayraksan, Erlon Cristian Finardi

Introduction

The optimal operation of energy systems aims to ensure the reliability of electricity supply while minimizing operational costs. This work focuses on the long-term generation scheduling (LTGS) problem for hydro-dominated power systems, where the uncertainty is related to the availability of water for future hydroelectric generation. This uncertainty is modeled through a multi-stage scenario tree. The Stochastic Dual Dynamic Programming (SDDP) is the state-of-the-art method to solve the LTGS problem, which decomposes the multi-stage problem into smaller subproblems and solves them dynamically. Despite advancements in modeling and solution strategies, significant issues remain concerning the distributions of inflows (and other random variables), especially with climate change. First, even though time series or other statistical methods are used to model these random parameters, the true probability distribution is never fully known. Furthermore, historical values used to devise statistical models may no longer be valid as processes shift. We focus on handling the effects of climate change in the LTGS problem by incorporating climate projection scenarios into the optimization problem and evaluating the performance of risk strategies, such as Conditional Value at Risk (CVaR) and Distributionally Robust Optimization (DRO).

Objectives

This work aims to handle the impact of climate change in the LTGS problem. The specific objectives are: Understanding the impacts of climate change on the operations of the electrical system by incorporating climate change projections into the scenario tree optimization; Evaluating the effectiveness of policies derived from different risk-averse metrics in protecting the system against climatic events.

Methodology

To understand the impacts of climate change in the LTGS problem, we first obtained climate projections regarding four climate models (MIROC5, CanESM2, HadGEM2, and BESM) under two Representative Concentration Pathways (RCP 4.5 and RCP 8.5). The data obtained refers to a representative part of the Brazilian Power System, which will be the focus of this study. After acquiring the data, we incorporated it into the optimization scenario tree, allowing the evaluation of the effects of extreme climatic events on the system's operations. The methodology also included the application of risk-averse metrics, such as CVaR and DRO, to analyze the system's behavior in adverse scenarios and evaluate the effectiveness of the policies generated in protecting against climate risks. This methodological approach allowed for a comprehensive view of how to improve the system's operational efficiency and increase the resilience of long-term energy planning.

Results and Discussion

Incorporating projections from different climate models revealed significant variations in inflows for different regions of Brazil, highlighting a possible increase in inflows in the South region and a decrease in other regions over the coming decades. It was shown that ignoring climate change in optimization scenarios increased the costs of the most expensive scenarios by up to 50%. The evaluation of risk strategies showed that both CVaR and DRO produced satisfactory results in protecting against climate risks. The DRO method presented smoother marginal costs and easier calibration, indicating greater effectiveness in dealing with projected uncertainties. The proposed strategies enhance the resilience of the electrical system under climate change scenarios, contributing to a more sustainable long-term energy planning.

Keywords: Climate change, SDDP decomposition, long-term electricity system planning, risk measures, hydropower.