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Robust Energy Seasonalization Strategy in the Brazilian Electricity Market

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Abstract:- The physical guarantee of a power generation plant corresponds to the minimum amount of energy that the plant can guarantee in an unfavorable scenario of inflows, based on historical data. It is, therefore, the amount of energy that the plant can commit in its sales contracts or self-consumption. The rules of the Brazilian electricity market allow a seasonal distribution of the physical guarantee of each plant. Seasonalization process consists in converting the average annual values of the plant physical guarantee into monthly values. The generator must declare the seasonalization of the physical guarantee annually, in December, at the Electric Energy Commercialization Chamber (CCEE). The decision on how to realize the seasonalization over the following year is made in an uncertain environment, as it depends on unknown initial data, such as future energy prices and the allocations of the Energy Reallocation Mechanism (MRE). This work proposes a strategy for seasonalization of the physical guarantee of a set of power generation plants based on models of multicriteria decision-making under information uncertainty.

Keywords:- *Energy seasonalization, multicriteria decision making, uncertainty factor, robust solutions, general decision making scheme.*

I. INTRODUCTION

The Brazilian electric system has more than 170 GW of installed power generation capacity, totaling more than 8 thousand electricity generation plants, according to information from the National Electric Energy Agency (ANEEL) [1]. Of all this capacity, more than 60% corresponds to hydraulic plants.

The predominance of hydroelectric plants in the Brazilian electrical system brings a strong dependence on inflows and reservoir levels. In addition, the fact that the power plants are often located in a cascade on the same river and belong to different agents brings even more complexity to the operation of this system, since the generation of a plant directly impacts the operation of the power plant downstream. The National System Operator (ONS) is the institution responsible for the operation and centralized dispatch of generation, with the objective of optimizing the national system in a neutral manner, as established in the Brazilian Decree Nº 5.081 of 2004 [2].

For each plant, a physical guarantee amount is determined. It corresponds to the minimum amount of energy that it can guarantee in an unfavorable scenario of inflows, based on historical data. Therefore, the physical guarantee is the amount of energy that the plant can commit in its sales contracts within the energy market. However, as the generation decision is elaborated centrally by ONS, situations in which a plant has generated, at a given time, less than the amount negotiated in contracts are common. This difference must be financially settled in the short-term market through the energy spot price.

In order to share the disadvantages and benefits, arising from a centralized dispatch decision, between all plants, the Energy Reallocation Mechanism (MRE) was put in place by Decree Nº 2.655 of 1998 [3]. In MRE, the sum of the generation of all participating plants is compared with the sum of all physical guarantees. Thus, the excess energy from plants that is generated beyond their physical guarantee is indeed in the plants generated below.

Electric Energy Commercialization Chamber (CCEE) performs monthly the accounting of energy traded in the national system. For this reason, the physical guarantee of the plants, which consists of an annual amount, must be distributed over the months of the year. This process takes place annually in December, when the generators must declare their seasonal physical guarantee for the following year. The decision on how to realize the seasonalization is taken in an uncertain environment, as it depends on unknown initial data, such as the power generation by the plant, the allocations from the MRE and the future energy spot price. In this way, power generation agents define their physical guarantee seasonalization strategies with the objective of minimizing their costs against the risks of short-term market exposures.

This work proposes a strategy for seasonalization of the physical guarantee of a set of power generation plants based on models of multicriteria decision making under conditions of uncertainty.

II. THEORETICAL REFERENCE

The physical guarantee seasonalization problem related to the Brazilian electricity market, risk analysis and decision-making under conditions of uncertainty concepts. In this section, the main concepts involved on the proposed solution are presented.

A. Physical Guarantee

The physical guarantee of the electrical system is the maximum amount of energy that the system can supply, considering a certain supply guarantee criterion, according to [4]. It is a concept used on the energy planning process with the objective of guaranteeing the energy supply even in unfavorable hydrological scenarios.

The total physical guarantee of the electrical system is prorated between the hydro power generation plants and this amount represents, from the commercial perspective, the maximum energy a power plant can negotiate, according to the Brazilian Decree Nº 5.163 [5].

Each power plant physical guarantee is an average annual amount established in the concession contract or in the authorization act and reviewed by the Brazilian Ministry of Mines and Energy (MME) every five years. The seasonalization of the physical guarantee is the distribution of this annual value among monthly amounts. This process is realized by the power generation agents participating in the MRE, which declare their seasonal physical guarantee for the following year.

The Brazilian legislation establishes that the sum of the monthly amount of physical guarantee in MWh cannot exceed the value of the annual physical guarantee in MWh. Additionally, the monthly seasonalized physical guarantee values cannot be higher than the installed capacity of the plant. Following these rules, the agents are free to define their seasonalization strategy, which can provide significant revenue gains. On the other hand, the agent's expected revenue is strongly related to the energy spot price, the agent's power generation and energy allocations in the MRE, components that are difficult to predict. Therefore, the seasonalization of the physical guarantee is a tool that allows both the mitigation of the risks of exposure to the short-time market, as well as the possibility of expanding the agent's revenue.

B. *Energy Reallocation Mechanism*

The power generation and transmission facilities in Brazil are operated by the ONS. ONS is responsible for programming the operation of the national system, defining the dispatch of the generation based on the availability of the plants. However, the best global dispatch solution of the system does not always correspond to the best solution from the individual point of view of power plant and their agents. Consequently, the hydro generation agents have no control over their generation level, despite making their sales commitments based on their physical guarantee. For this reason, there is a risk of not generating the total amount of energy committed in contracts.

The MRE was created to share hydrological risk between the hydroelectricity plants. Participation in the mechanism is mandatory for hydroelectric plants dispatched by ONS and optional for Small Hydroelectric Plants (PCH).

In the processing of MRE, carried out monthly, the amount of energy generated by the mechanism plants is compared with the total physical guarantee amount of the plants belonging to the mechanism, resulting in the Generation Scaling Factor (GSF), presented as follows:

$$GSF_m = G_{MRE_m} / GFIS_{MRE_m} \quad 1)$$

where GSF_m is the Generation Scaling Factor for themonth$m$, G_{MRE_m} is the energy generated by the mechanism plants for the month m and $GFIS_{MRE_m}$ representes the total physical guarantee of MRE for the month m.

There are three possible scenarios in the MRE: equilibrium scenario, secondary energy scenario and physical guarantee adjustment scenario. In the equilibrium scenario, the total physical guarantee of the mechanism is equal to the total generation, resulting in a GSF_mequal to one.

In the Secondary Energy scenario, the total generation of the mechanism is higher than the total physical guarantee, resulting in a GSF_mgreater than one. The difference between the total energy generated and the total physical guarantee is allocated to the deficit plants. At the end of this process, there will be a surplus of energy, called Secondary Energy. Secondary Energy is divided among all plants participating in the MRE in proportion to their physical guarantees. This scenario represents the sharing of the benefit among the power plants that participates of the MRE.

In the third scenario, where the adjustment of the physical guarantee occurs, the total generation of the MRE is smaller than the total physical guarantee. The difference between the physical guarantee of the mechanism and the generation is prorated between the plants, decreasing the individual physical guarantees. This scenario represents the sharing of losses between the plants that participates of the MRE.

C. *NEWAVE*

The Brazilian electrical system is characterized as a predominantly hydro-thermal and interconnected system. The operation of a system with these characteristics is realized in an integrated manner, optimizing the operation of all plants in order to obtain synergistic gains for the system, as described in [6]. ONS is the institution of the electric sector responsible for the operation of the system, carrying out the planning, programming and operation in real time of the system.

NEWAVE, a planning model for the operation of interconnected hydro-thermal systems for the long and medium term, was developed by the Electric Energy Research Center (Cepel) and is currently applied in planning the operation and expansion of the Brazilian electrical system. In this model, hydrological uncertainties are represented by hydrological scenarios constructed synthetically by a periodic auto-regressive model [16]. Therefore, for the generated synthetic hydrological scenarios, the model calculates the future electrical generation dispatch, the energy exchanges between the subsystems and, as a consequence, the expected cost of the defined operating policy.

NEWAVE is the official model used by the institutions of the Brazilian electrical system to determine the Ten-Year Energy Expansion Plan (PDE), Monthly Operation Program (PMO) and Energy Operation Plan (PEN), energy spot price calculation, calculation of physical guarantee and the assured energy of generation projects and definition of guidelines for Brazilian energy auctions [6]. As NEWAVE is part of the official models for defining the operating policy and spot prices, it will be used in this work to obtain the GSF and spot prices for each of the 2.000 synthetic series of flows generated by the model.

D. Conditional Value at Risk

The possibility of involuntary exposure to short-time market and to highly volatile prices brought the need to improve the decision-making process for energy commercialization, with risk analysis and management tools being incorporated into the process.

Conditional Value-at-Risk (CVaR), also known as mean excess loss, mean shortfall or tail VaR, was proposed by [7]. CVaR is a risk measure introduced as an evolution of the concept of Value-at-Riks (VaR). VaR is the measure of the maximum potential loss of a portfolio for a given level of confidence. The VaR measure, however, does not consider the potential losses higher than its value, which can become significant. CVaR brings in its value the average loss that exceeds VaR, including the tail of the probability distribution, making it possible to measure the worst scenarios.

Due to the fact that it also covers the worst observations, CVaR is a more conservative risk metric when compared to VaR. For this reason, CVaR has been widely used in the Brazilian electricity sector in official computational models responsible for dispatch and pricing. Thus, in this work, the CVaR metric will be used to calculate the risk associated with each seasonalization strategy.

E. Multicriteria decision making under conditions of uncertainty

Multicriteria decision-making is associated with decision-making in the presence of multiple and conflicting criteria and can be classified into two groups, as described by [8]: multi objective problems and multi attribute problems.

Multi objective decision-making is considered the continuous type of multicriteria decision-making, since it concentrates on continuous decision spaces. Solving continuous problems of multicriteria decision-making involves the design of alternatives that optimizes or satisfies the decisionmaker objectives [8]. The decision maker must maximize or minimize multiple, non-commensurable and conflicting objectives. A multi objective decision-making model is composed of a vector of decision variables, objective functions and constraints.

In multi attribute decision-making problems, the decision space is discrete, since it is related to decision making of preferences about the available alternatives, characterized by multiple attributes and, generally, conflicting [8]. Multi attribute decision-making problems involve the selection of the “best” alternative froma pool of preselected alternatives [18].

Based on the particular characteristics of these two groups of multicriteria problems, [9] proposed two different models for decision-making: <X,F> for multi objective problems and <X,R> for multi attribute problems. In agreement with the multi objective nature of the problem studied in this work, the <X, F> model will be described and applied.

F. <X,F> model

Multi objective decision-making is formed by an objective function vector$F(X) = \{f_1(X), f_2(X), \dots, f_q(X)\}$that must be simultaneously optimized, i.e.,

$$F_p(X) \rightarrow \underset{X \epsilon L}{extr}, \quad p = 1,2, \dots, q \tag{2}$$

where q ≥ 2 and L is a set of feasible solutions in R^n.

Bellman and Zaddeh proposed in [10] a method for decision-making in a fuzzy environment in 1970. Decision-making in a fuzzy environment can be understood as a decision process which objectives or restrictions are fuzzy in nature, that is, its limits are not clearly defined. P. Ekel complemented, in [9],Bellman-Zaddeh approach to apply it in analyzing multi objective decision-making problems.

When applying the Bellman-Zaddeh approach to multiobjective decision-making process, each objective function$F_p(X)$is replaced by a fuzzy objective function or fuzzy sets:

$$A_p = \{X, \mu_{A_p}(X)\}, \quad X \epsilon L \tag{3}$$

where$\mu_{A_p}(X)$is the membership function level of the solution $X$to the fuzzy setA_p.

Thus, a fuzzy solution$D = \bigcap_{p=1}^{q} A_p$is obtained with a membership function

$$\mu_D(X) = \min_{p=1,2,..q} \mu_{A_p}(X), \qquad X \epsilon L. \tag{4}$$

The use of (4) allows one to obtain a solution that provides the maximum degree of belongingness to the fuzzy solution D, as follows:

$$\max \mu_D(X) = \max_{X \in L} \min_{p=1,2,\dots,q} \mu_{A_p}(X). \tag{5}$$

The multicriteria problem, described in (2), can be reduced to a search for a solution

$$X^0 = \arg \max_{X \in L} \min_{p=1,2,\dots,q} \mu_{A_p}(X). \tag{6}$$

The membership function$\mu_{A_p}(X)$is expressed by (8) for maximized objective functions, or by (9) for minimized objective functions:

$$\mu_{A_p}(X) = \left[\frac{F_P(X) - \min F_P(X)}{\max F_P(X) - \min F_P(X)}\right]^{\lambda_p}, \tag{7}$$

$$\mu_{A_p}(X) = \left[\frac{\max F_P(X) - F_P(X)}{\max F_P(X) - \min F_P(X)}\right]^{\lambda_p}, \tag{8}$$

where$\lambda_p, p = 1,2, \dots, q$ are importance factors defined by the decision maker. These weighting factors represents the relative importance between the objective functions.

G. Uncertainties in the decision-making process

In decision-making process, it is not always easy to obtain data and initial information in sufficient volume and in the quality necessary for modeling the problem. Considering the uncertainties in the construction of mathematical models increases their suitability for the problem, the credibility and real efficiency of the decisions resulting from the analyzes.

In order to deal with uncertainties in decision making, [11] and [12] proposed an approach that combines two branches of mathematics that deal with uncertainties: game theory and fuzzy set theory. Representative combinations of initial data, states of nature or scenarios are created in order to reduce the decision uncertainty region.

The works developed by [13] and [14] present results of this approach in engineering and resource allocation problems. The method used is based on a possibilistic approach as a generalization of the classical approach proposed in [15] and [16], and will be presented below.

H. Generalization of the classic approach to dealing with the uncertainty information to multicriteria decision making process

Generalizing the classical approach to decision-making in conditions of uncertainty, initially, the solution alternatives for each scenario$S$are obtained using the <X,F> model. From the set of$S$solutions obtained, a subset of$K$ solutions$X_k, k = 1,2, \dots, K$ is selected to construct the payoff matrix of each objective function. Thus, the$X_k, k = 1,2, \dots, K$,solutions for each of the$Y_s, s = 1,2, \dots, S$,scenarios must be applied to each of the objective functions$F_p(X, Y_s), p = 1,2, \dots, q$, generating a payoff matrix for each objective function, as presented in Tab. 1.

	Y_1	$\cdots$	Y_s	$\cdots$	Y_S
X_1	$F_p(X_1, Y_1)$	$\cdots$	$F_p(X_1, Y_s)$	$\cdots$	$F_p(X_1, Y_S)$
$\vdots$	$\vdots$		$\vdots$		$\vdots$
X_k	$F_p(X_k, Y_1)$	$\cdots$	$F_p(X_k, Y_s)$	$\cdots$	$F_p(X_k, Y_S)$
$\vdots$	$\vdots$		$\vdots$		$\vdots$
X_K	$F_p(X_K, Y_1)$	$\cdots$	$F_p(X_K, Y_s)$	$\cdots$	$F_p(X_K, Y_S)$

Table 1: Payoff Matrix

Subsequently, the choices criteria of Wald, Laplace, Savage and Hurwicz are used as objective functions of the problem, as proposed in [4], [5] and [6]:

$$F^W(X_k) = F^{max}(X_k) = \max_{1 \le s \le S} F(X_k, Y_s) \quad (9)$$

$$F^L(X_k) = \bar{F}(X_k) = \frac{1}{S}\sum_{s=1}^{S} F(X_k, Y_s) \quad (10)$$

$$F^S(X_k) = R^{max}(X_k) = \max_{1 \le s \le S} R(X_k, Y_s) \quad (11)$$

$$F^H(X_k) = \alpha F^{max}(X_k) + (1-\alpha) F^{min}(X_k) = \alpha \max_{1 \le s \le S} F(X_k, Y_s) + (1 - \alpha) \min_{1 \le s \le S} F(X_k, Y_s). \quad (12)$$

Therefore, it is possible to build$q$problems including up to four objective functions related to the choices criteria:

$$F_{r,p}(X) \rightarrow \underset{X \in L}{extr}, \quad r = 1,2, \dots, M \le 4, \quad p = 1,2, \dots, q, \quad (13)$$

where the objective functions are$F_{1,p}(X) = F_p{}^W$, $F_{2,p}(X) = F_p{}^L$, $F_{3,p}(X) = F_p{}^S$, $F_{4,p}(X) = F_p{}^H$.

Applying (14) to q payoff matrices, it is possible to build matrices with the choices criteria, as shown in Tab. 2.

	$F_p{}^W(X_k)$	$F_p{}^L(X_k)$	$F_p{}^S(X_k)$	$F_p{}^H(X_k)$
X_1	$F_p{}^W(X_1)$	$F_p{}^L(X_1)$	$F_p{}^S(X_1)$	$F_p{}^H(X_1)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
X_k	$F_p{}^W(X_k)$	$F_p{}^L(X_k)$	$F_p{}^S(X_k)$	$F_p{}^H(k)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
X_K	$F_p{}^W(X_K)$	$F_p{}^L(X_K)$	$F_p{}^S(X_K)$	$F_p{}^H(X_K)$
	$\min_{1 \le k \le K} F_p{}^W(X_k$	$\min_{1 \le k \le K} F_p{}^L(X_k$	$\min_{1 \le k \le K} F_p{}^S(X_k$	$\min_{1 \le k \le K} F_p{}^H(X_k$
	$\max_{1 \le k \le K} F_p{}^W(X_k$	$\max_{1 \le k \le K} F_p{}^L(X_k$	$\max_{1 \le k \le K} F_p{}^S(X_k$	$\max_{1 \le k \le K} F_p{}^H(X_k$

Table 2: Payoff Matrix With Choice Criteria Estimates For The Pth Objective Function

Using the$q$choice criteria matrices and applying (7) or (8),as proposed in [12], [13] and [14], modified matrices are built, as shown in Tab. 3.

Applying (4) to the modified matrices, it is possible to construct the aggregated payoff matrix, as presented in Tab. 4.

Finally, (6) is used to obtain the best solution alternative for each choice criterion.

	$\mu_{A_p}{}^W(X_k)$	$\mu_{A_p}{}^L(X_k)$	$\mu_{A_p}{}^S(X_k)$	$\mu_{A_p}{}^H(X_k)$
X_1	$\mu_{A_p}{}^W(X_1)$	$\mu_{A_p}{}^L(X_1)$	$\mu_{A_p}{}^S(X_1)$	$\mu_{A_p}{}^H(X_1)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
X_k	$\mu_{A_p}{}^W(X_k)$	$\mu_{A_p}{}^L(X_k)$	$\mu_{A_p}{}^S(X_k)$	$\mu_{A_p}{}^H(X_k)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
X_K	$\mu_{A_p}{}^W(X_K)$	$\mu_{A_p}{}^L(X_K)$	$\mu_{A_p}{}^S(X_K)$	$\mu_{A_p}{}^H(X_K)$

Table 3: Modified Matrix of Choice Criteria Estimates for the Pth Objective Funcion

	$\mu_D{}^W(X_k)$	$\mu_D{}^L(X_k)$	$\mu_D{}^S(X_k)$	$\mu_D{}^H(X_k)$

X_1	${\mu_D}^W(X_1)$	${\mu_D}^L(X_1)$	${\mu_D}^S(X_1)$	${\mu_D}^H(X_1)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
X_k	${\mu_D}^W(X_k)$	${\mu_D}^L(X_k)$	${\mu_D}^S(X_k)$	${\mu_D}^H(X_k)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
X_K	${\mu_D}^W(X_K)$	${\mu_D}^L(X_K)$	${\mu_D}^S(X_K)$	${\mu_D}^H(X_K)$

Table 4: Aggregated Payoff Matrix of Choice Criteria Estimates

III. METHODOLOGY

The seasonalization of the physical guarantee of a self-producing power generation agent that owns a set of plants belonging to the Energy Reallocation Mechanism will be treated as a multi objective problem which aims to allocate the annual physical guarantee throughout the months of the year. The seasonalization strategy will be proposed in order to minimize its costs and minimize the risks of revenues lost in the energy market.

In the following sections, the objective functions that represent the expected cost and risk as well as the modeled constraints for the problem are presented.

A. Objective function: Cost

The total cost of a self-producing energy agent that owns hydroelectric generation plants belonging to the MRE is made up of four installments, according to (14): cost related to operations in the short-time market (C_{MCP}), cost of long-term contracts (C_{cont}), energy charges (C_{enc}) and the collection of ICMS - Tax on Circulation of Goods and Services (C_{ICMS}):

$$C_{ser} = C_{MCP_{ser}} + C_{cont_{ser}} + C_{enc_{ser}} + C_{ICMS_{ser}}. \qquad (14)$$

The expected cost for this agent is given by the average of the simulated series, as follows:

$$C_{exp} = \frac{1}{nSer}\sum_{1}^{nSer} C_{ser}, \qquad (15)$$

where $nSer$ is the total number of series used in the simulation.

B. Cost related to the short-time market operations

CCEE performs the accounting of energy traded in the Brazilian energy market by comparing the amounts of verified and contracted energy amounts. This process is carried out individually for each agent and the differences between the verified and contracted amounts are computed as transactions in the short-time market and will be valued by the spot price.

The verified energy is composed of the agent's measured generation or consumption, considering the MRE's energy allocations. The contracted energy is associated with the agent's net contractual position, that is, it is the difference between the total sales contracts and the total purchase contracts of the agent.

The verified energy for each submarket and simulated series obtained from NEWAVE is given by

$$VE_{ser,sub} = \sum_{i=1}^{I}\sum_{m=1}^{12}\left(g_i \cdot GSF_{ser,m} \cdot x_{i,m} + C_{C_{m,sub}}\right), \qquad (16)$$

where g_i is the annual physical guarantee of the plant i, $GSF_{ser,m}$ is the Generation Scaling Factor of the month m of the NEWAVE series ser, $x_{i,m}$ is the seasonalization factor and $C_{C_{m,sub}}$ is the volume of the purchase contract for the month m and submarket sub.

The contracted energy is calculated as follows:

$$CE_{sub} = \sum_{m=1}^{M}\left(l_{m,sub} + C_{v_{m,sub}}\right) \qquad (17)$$

where $l_{m,sub}$ is the load for the month m located in the submarket m, $C_{v_{m,sub}}$ represents the volume of purchase contract for the month m in the submarket sub.

The agent's exposure to the MCP is the difference between verified and contracted amounts of energy. For example, if the agent does not have sufficient energy generation to meet his requirements contracts, an exposure is verified and will be valued by the spot price ($p^{spot}_{sub,ser}$) of the corresponding submarket. Therefore, the cost related to the short-time market operations is given by:

$$C_{MCP_{ser}} = \sum_{sub=1}^{4}\left(VE_{ser,sub} - CE_{sub}\right) \cdot h_m \cdot p^{spot}_{sub,ser} \qquad (18)$$

where h_m is the number of hours of month m.

C. Long-term contracts costs

The cost for long-term energy contracts for each simulated series represents the agent's net contractual cost, and can be obtained as follows:

$$C_{cont_{ser}} = \sum_{sub=1}^{4}\left(C_{C_{m,sub}} \cdot h_m \cdot P_{C_c}\right) - \left(C_{v_{m,sub}} \cdot h_m \cdot P_{C_v}\right) \qquad (19)$$

where P_{C_c} and P_{C_v} are the prices of the respective purchase and sale contracts.

D. Cost of energy charges

Electricity charges are included in the portion of the Distribution System Use Tariff (TUSD) applied to energy consumption.

For a self-producing agent, the TUSD referring to energy charges will only apply to the portion of consumption not met by self-production. This consumption not met by self-production depends on the amount of physical guarantee allocated for each month of the year. In addition, self-production should be distributed among the agent's consumer units, if the agent has different loads.

The calculation of charge costs was modeled as an optimization subproblem where the self-produced energy must be allocated for the agent loads, minimizing the cost of charges, described as:

$$C_{enc_{ser}} = \sum_{m=1}^{12}\sum_{l=1}^{L}\{v_l \cdot h_m[\alpha_{l,m} \cdot e_l + (1-\alpha_{l,m}) \cdot E_l]\}, \quad (20)$$

where:

$$e_l = 0{,}125 \cdot T_{l,P}^{APE} + 0{,}875 \cdot T_{l,FP}^{APE}, \quad (21)$$

$$E_l = 0{,}125 \cdot T_{l,P} + 0{,}875 \cdot T_{l,FP}, \quad (22)$$

$$\alpha_{l,m} = \frac{a_{l,m}}{v_l}, \quad (23)$$

subject to:

$$\sum_{l=1}^{L} a_{l,m} = A_{m,ser}, \quad (24)$$

$$A_{m,ser} = \sum_{i=1}^{I} g_{i,ser} \cdot GSF_{m,ser} \cdot x_{i,m}, \quad (25)$$

$$0 < \alpha_{l,m} \leq 1. \quad (26)$$

where v_l is the volume of load l, $\alpha_{l,m}$ is the proportion of the load supplied by self-produced energy, $a_{l,m}$ is the self-produced energy allocated for the load l in the month m, $A_{m,ser}$ represents the total self-produced energy in the month m for the series ser, e_l and $E_l$correspond to the tariff for charges for a self-producing agent and a conventional agent respectively.

E. ICMS cost

The tax on Circulation of Goods and Services (ICMS) is levied on the resources of the self-producing energy agent. Thus, the allocation of the agent's resources must be carried out in order to minimize the ICMS costs and it was modeled as an optimization subproblem, as follows:

$$C_{ICMS_{ser}} = \sum_{e}^{E} ICMS_e \cdot \sum_{i}^{I} \tau_{e,i,ser} \cdot r_{e,i} \cdot R_{e,i} \quad (27)$$

where:

$$\tau_{i,t} \in \{OM_i, p_{sub,ser}^{spot}\} \quad (28)$$

$$R_i \in \{g, x, Exp(x)\} \quad (29)$$

subject to:

$$0 \leq r_{e,i} \leq 1 \quad (30)$$

$$\sum r_{e,i} \leq 1 \forall i, \quad (31)$$

$$\sum r_{e,i} \cdot R_{e,i} = R_{eq,e}, \quad (32)$$

where$ICMS_e$is the ICMS rate for the state$e$, $R_{e,i}$is the resource of each state,$r_{e,i}$represents the allocation factor, OM_icorresponds to the cost of operating and maintaining the asset$i$ and $Exp(x)$consists of exposure at the short-time market.

F. Objective function: Market risk

The CVaR risk metric applied to the cost distribution of the simulated series in NEWAVE is the average cost of the β worst distribution scenarios, as shown:

$$CVaR = \frac{1}{\beta \cdot nSer} \sum_{ser=1}^{\beta \cdot nSer} C_{ser} \quad (33)$$

G. Constraints

The seasonatization of the physical guarantee must respect certain restrictions, according to the Brazilian normative resolution ANEEL Nº584 of 2013 [17]. The physical guarantee allocated for each month must not exceed the installed power of the plantP_i, according to (34). In addition, the sum of the monthly allocations of each plant must be equal to its annual physical guarantee, presented in (35):

$$0 \leq g_{i,m} \cdot x_{i,m} \leq P_i, \quad (34)$$

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$$g_i = \sum_{m=1}^{12} g_{i,m} \cdot x_{i,m}. \qquad (35)$$

STUDY CASE

The simulation considered a self-producing energy agent whose hydraulic plants, loads and long-term contracts are described in Tab. 5, Tab. 6 and Tab. 7.

Plant	Submarket	Installed Capacity [MW]	Physical Guarantee [MWmed]	O&M Cost [R$/MWh]
1	Southeast	10,685	4,420	0,53
2	Southeast	29,232	19,990	0,53
3	Southeast	12,800	7,000	0,53
4	Southeast	70,000	32,650	0,53
5	North	326,100	192,324	0,53

Table 5: Self-Producing Agent Plants

Load	State	Submarket	Volum [MW]	Subgroup	Tariff Mode
1	MG	Southeast	130	A4	Green
2	MS	Southeast	69	A4	Green
3	PB	Northeast	214	A4	Green

Table 6: Self-Producing Agent Loads

Contract	Type	Submarket	Volum [MWmed]	Price [R$/MWh]
1	Purchase	Southeast	63	100
2	Purchase	Southeast	76	105
3	Purchase	North	30	98,50
4	Sale	Southeast	15	130
5	Sale	North	15	110

Table 7: Self-Producing Agent Loads

As scenarios for decision-making, the results of the Monthly Energy Operation Program (PMO), carried out by ONS, were used. One of the products of the PMO are files of the NEWAVE model. Each of the seven scenarios used in this work is composed of 2,000 series of CMOs and hydraulic generation, which were treated to obtain the PLD and GSF series.

The algorithm presented in Fig. 1 was implemented in python to obtain the best alternative for the seasonal profile of the physical guarantee of the agent.

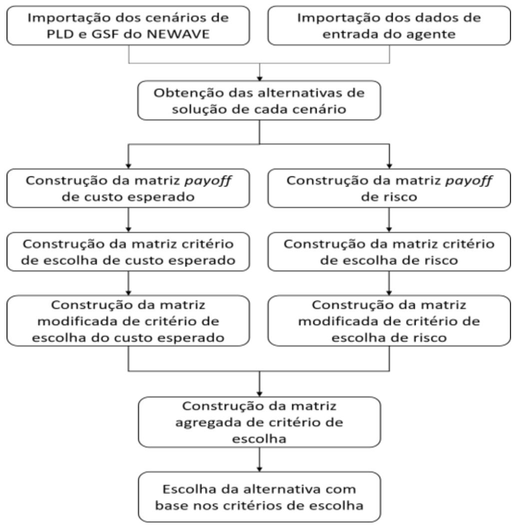

Fig. 1: Algorithm Scheme

The five solution alternatives chosen for the construction of the payoff matrices are found in Fig. 2. These strategies were predefined according to the seasonality of the wet and dry season in Brazil. This approach took into account the natural tendency for low prices to occur in the wet season and high prices in the dry season. TheX_1alternative represents the constant seasonalization of the physical guarantee over the horizon, also known as flat seasonalization. The profilesX_2 and X_3have a higher allocation in the months with most occurrence of rainfall. The alternativeX_4 have a higher allocation in the months with most occurrence of rainfall. The alternativeX_5 has a higher allocation at the beginning and end of the year.

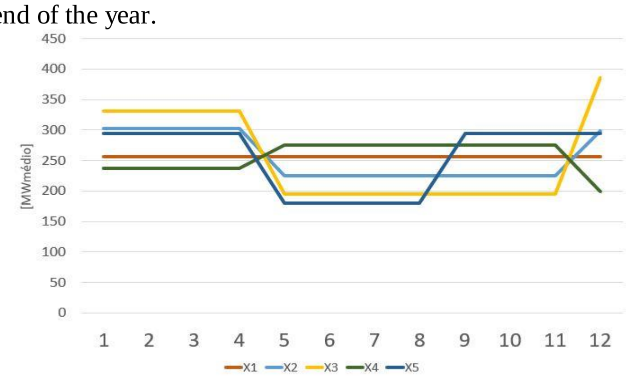

Fig. 2: Solution Alternatives

Thepayoff matrices were built for each of the objective functions based on the combination of the five alternative solutions chosen with the seven simulated scenarios. Tab. 8 and Tab. 9 present the cost and risk payoff matrices.

	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7
X_1	96.17	85.58	-36,12	-27.32	65.20	83.37	65.33
X_2	96.51	85.77	-45.89	-27.55	63.66	82.89	65.50
X_3	96.07	84.78	-83.56	-29.65	61.21	80.27	60.49
X_4	96.49	86.12	-21.24	-26.70	67.12	84.50	66.44
X_5	92.49	81.12	-57.82	-28.62	57.98	80.46	63.83

Table 8: Expected Cost Matrix

	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7
X_1	108.42	100.28	32.91	80.61	94.74	102.10	102.42
X_2	107.78	99.56	22.13	80.25	94.72	101.45	102.90
X_3	106.12	96.90	-4.36	104.4	95.52	98.55	102.37
X_4	109.77	101.54	49.03	86.46	95.25	103.18	102.41
X_5	104.27	95.42	19.32	92.15	94.70	100.89	104.44

Table 9: Expected Risk Matrix

Starting from the payoff matrices, the matrices of choices criteria for the cost and risk were obtained and the results are presented in Tab. 10 and Tab. 11.

	$F_1{}^W(X_k)$	$F_1{}^L(X_k)$	$F_1{}^S(X_k)$	$F_1{}^H(X_k)$
X_1	96.17	47.45	47.44	63.09
X_2	96.51	45.84	37.67	60.91
X_3	96.07	38.51	3.66	51.16
X_4	96.49	50.39	62.32	65.69
X_5	92.49	41.35	25.74	54.91

Table 10: Matrix of Choice Criteria for Expected Cost

	$F_2{}^W(X_k)$	$F_2{}^L(X_k)$	$F_2{}^S(X_k)$	$F_2{}^H(X_k)$
X_1	108.42	88.78	37.28	89.55
X_2	107.78	86.97	26.50	86.36
X_3	106.12	85.65	24.19	78.50
X_4	109.77	92.52	53.40	94.59
X_5	104.44	87.32	23.69	83.16

Table 11: Matrix of Choice Criteria for Expected Risk

The next step is to obtain the matrices of standardized choice criteria. For this step, the two objective functions were treated with the same importance coefficient$\lambda_p = 1$. The standardized selection criteria matrices are found in Tab. 12 and Tab. 13.

	$\mu_{A_1}{}^W(X_k)$	$\mu_{A_1}{}^L(X_k)$	$\mu_{A_1}{}^S(X_k)$	$\mu_{A_1}{}^H(X_k)$
X_1	0.08	0.24	0.25	0.17
X_2	0.00	0.38	0.42	0.32
X_3	0.11	1.00	1.00	1.00
X_4	0.00	0.00	0.00	0.00
X_5	1.00	0.68	0.49	0.74

Table 12: Modified Matrix of Choice Criteria for Expected Cost

	$\mu_{A_2}{}^W(X_k)$	$\mu_{A_2}{}^L(X_k)$	$\mu_{A_2}{}^S(X_k)$	$\mu_{A_2}{}^H(X_k)$
X_1	0.25	0.54	0.54	0.31
X_2	0.37	0.80	0.90	0.51
X_3	0.68	1.00	0.98	1.00
X_4	0.00	0.00	0.00	0.00
X_5	1.00	0.75	1.00	0.70

Table 13: Modified Matrix of Choice Criteria for Expected Risk

Finally, the aggregated matrix of the choice criteria is presented in Tab 14. Note that the Laplace, Savage and Hurwiczchoice criteria indicate the alternative X_3 as the best one. However, Wald's criterion indicates the X_5 solution.

	$\mu_D{}^W(X_k)$	$\mu_D{}^L(X_k)$	$\mu_D{}^S(X_k)$	$\mu_D{}^H(X_k)$
X_1	0.08	0.24	0.25	0.17
X_2	0.00	0.38	0.42	0.32
X_3	0.11	1.00	0.98	1.00
X_4	0.00	0.00	0.00	0.00
X_5	1.00	0.68	0.49	0.70

Table 14: Matrix With Aggregated Levels of the Fuzzy Choice Criteria.

TheX_3seasonalization strategy results in the average resource profile seen in Fig. 3 for the agent. Fig. 4 shows the cost distribution of theY_1scenario for theX_3seasonalization strategy. On the other hand, the seasonalization profileX_5produces the energy balance shown in Fig. 5 and the cost distribution of Fig. 6, for the scenarioY_1.

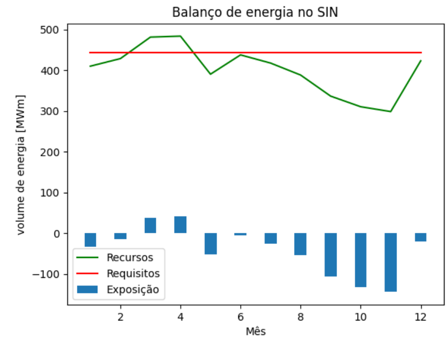

Fig. 3: Energy Balance for the Seasonalization profile X_3

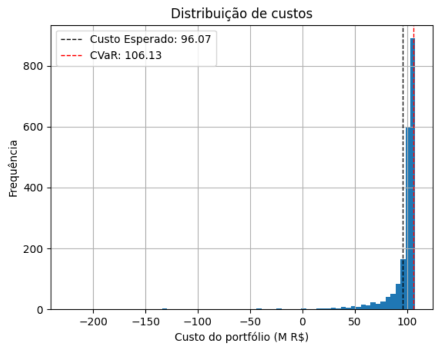

Fig. 4: Cost Distribution for the Solution X_3 Applied to Scenario Y_1

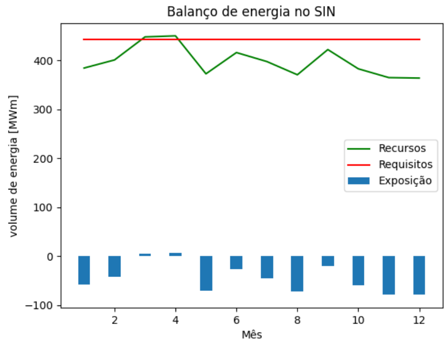

Fig. 5: Energy Balance for the Seasonalization profile X_5

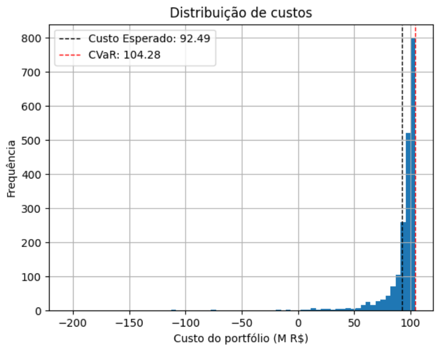

Fig. 6: Cost Distribution for the Solution X_5 Applied to Scenario Y_1

IV. CONCLUSIONS

In this work, the seasonalization of the physical guarantee of hydroelectric power plants belonging to the MRE was modeled as a multi objective decision making problem under conditions of uncertainty. The seasonality strategy was obtained with the objective of minimizing the agent's expected cost and its exposure to market risks.

The generalization method of the classical approach, proposed in [4], was used for the decision-making process and applied to an energy self-producing agent. As shown through the payoff matrices of the case study, the great variability of energy prices and GSF can generate different and, in some cases, opposite results for the same adopted seasonality strategy. This method application allows a problem modeling closer to reality and a more assertive decision-making process.

For the case study presented, the choice criteria of Wald, Laplace, Savage and Hurwicz indicated two possible solution alternatives. For cases where more than one alternative is found, the <X,R> model can be applied, in order to reduce the regions of uncertainty, being a proposal for future works.

In addition, as a continuation of the work, the definition of solution alternatives will be implemented based on the PLD and GSF scenarios obtained to replace the use of predefined alternatives.

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