Fostering Wind Power Penetration into the Brazilian Forward-Contract Market

Alexandre Street, *Member, IEEE*; Delberis A. Lima; Álvaro Veiga; Bruno Fânzeres; Lucas Freire; and Bianca Amaral

***Abstract*—Wind power generation plays an important role in most power systems worldwide. Despite that, only in 2009, wind farms appeared as a profitable and competitive investment option in Brazil. The Brazilian power system is mainly hydro based and, due to its many singularities, its coordination is still centralized. A collateral effect of such centralized dispatch coordination is that the system marginal costs, which determine the short-term energy prices, exhibit a highly volatile pattern. In this setting, selling energy through bilateral forward contracts backed up on intermittent generation profiles, such as wind farms and small-run hydros, exposes the generation company (Genco) to the so-called price-quantity risk. In this paper, we explore the well-known complementarity between these two renewable resources (wind and inflows) by proposing a statistical model capable to produce scenarios of renewable resources availability consistently with short-term price scenarios. Hence, we present a novel commercial model for a wind power producer based on a joint-selling strategy with a small-hydro Genco. In this model, the hydro Genco receives a surplus payment in comparison to the amount it would receive in the market and the wind Genco, the rest of the income. We show, by means of realistic data from the Brazilian power system, that such commercial model is able to mitigate the exposure to the short-term price and foster the wind power penetration into the contract market.**

***Index Terms*— Conditional Value-at-Risk, forward contract, wind power generation, hydroelectric power generation, risk-aversion, renewable energy.**

I. Introduction

WIND power is consolidated in many power systems worldwide. Despite that, only in 2009 such technology appeared in the Brazilian power system as a competitive option for investors. The main reasons for that are twofold. First, the world financial crisis has promoted a widespread investment cutoff in Europe. In this scenario, European and Asian manufacturers, aiming to find an alternative market, have started to change their focus to still growing economies, which is the case of Brazil. The second reason lies in the Brazilian regulatory environment, which has recently been adjusted to alleviate wind power producer risks in the Regulated Trading Environment (RTE).

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Alexandre Street, Delberis A. Lima, Álvaro Veiga, Bruno Fânzeres, Lucas Freire, and Bianca Amaral are with the Electrical Engineering Department of PUC-Rio, Rua Marquês de São Vicente 225, Ed. Cardeal Leme, Sala L401 – Gávea – Rio de Janeiro – Brazil – 22451-900 (e-mail: {street, delberis, alvf}@ele.puc-rio.br).

In the Brazilian power system, two different trading environments coexists: the RTE, where distribution companies (Discos) purchase medium and long-term bilateral contracts through public open auctions (see [2] and references therein) and the Free Trading Environment (FTE), where consumers and generation companies (Gencos) freely negotiate energy mainly through standard forward contracts. While the former still represents the major market in terms of energy (about 70%), the latter has been gaining substantial attention in the last five years, especially regarding renewable energy trade. The main reason for that is an incentive, discount of 50% in the transmission fee, for consumers that purchase renewable energy in such market. The main challenge faced by a wind power producer (WPP) when selling energy in the FTE is that their production profile through the year is intermittent and quite seasonal.

The Brazilian power system is mainly hydro based and, due to its many singularities, its coordination is still centralized. A stochastic dual dynamic programming approach is employed in order to dispatch generators based on the reservoir water opportunity cost for the system (see [4]). However, a collateral effect of such centralized dispatch coordination is that system marginal costs, which determine the short-term energy prices, exhibit a highly volatile pattern [3]. Therefore, selling energy through a forward contract backed up on wind power production exposes the WPPs to the so-called price-quantity risk, which occurs whenever the seller is long in contracts and must purchase in the short-term market, at high prices, the amount (quantity) sold but not produced.

In [1], the optimal portfolio composed of a small run-of-river hydro (SH) and a biomass (from sugar-cane waste) cogeneration power plant is established to back up a forward contract sell at the FTE. The main motivation for this strategy is that the biomass and the SH generation profiles are complementary. Thus, a portfolio with these two sources is able to mitigate the price-quantity risk by reducing the final portfolio seasonality. The objective of the present work, notwithstanding, is to foster the penetration of WPPs into the FTE. Therefore, we extend the results found in [1] to consider a WPP in the portfolio, aiming to provide it with a safer entrance into such environment. To do that, we propose a scenario generation methodology capable to produce dependent scenarios of wind and hydro generation consistently with short-term price scenarios simulated by the dispatch model. Since all SHs and WPPs are marginal to the Brazilian power system, the uncertainties present on their generation profiles are not accounted into the system dispatch model. In that sense, to create a link between short-term price scenarios and generation scenarios of marginal wind farms and SH plants, a heteroscedastic conditional vector auto-regressive model is proposed. We argue that only by means of such dependent scenarios one is able to quantify the price-quantity risk for contracts backed up on intermittent generation profiles, such as wind farms and SHs. Thus, the contributions of this work are twofold:

1. promote a safer entrance into the FTE for WPPs by means of a renewable portfolio-based commercial model;
2. provide investors, trading companies and Gencos with an analytic simulation tool capable to produce scenarios of intermittent renewable generation profiles consistently with energy short-term price scenarios provided by the system dispatch simulation model;

In addition, results will be illustrated by means of a case study with realistic data from the Brazilian power system.

The rest of this work is organized as follows. In section II, we provide a contextualization of the Brazilian power system in order to substantiate the problem and establish the basic concepts that are used throughout the paper. In section III, the portfolio-based commercial model is introduced and, in section IV, the proposed methodology that provides the portfolio problem with wind and hydro generation scenarios consistent with a system dispatch simulation are presented. Finally, in section V, our case study is presented and, in section VI, the main conclusions and considerations are drawn.

II. Overview of the Brazilian Power System

Nowadays, the main challenge faced by power system regulators is to ensure an efficient and clean generation expansion that can provide reliable energy to all consumers with a “fair” energy price. This challenge also includes the setting of the correct incentives to allow the entrance of new generation capacity in order to meet the load growth, especially in emerging markets like the Brazilian one.

After the 2002 supply crisis [14][3], the Brazilian power system regulatory rules were reformed [3]. This new regulatory framework states that every load, for both captive and free consumers, must be 100% contracted. This obligation provides a link between the physical generation expansion and the load growth: although these contracts are entirely financial, they should be covered by firm energy certificates (FEC), which means that, if 100% of the demand is contracted, there must exist an equivalent physical generation that supplies the correspondent load even under low system resources. Therefore, it guarantees that the load growth and the physical generation expansion walk hand in hand.

The national regulator issues a FEC to each new power plant and revises it every five years. These certificates define the maximum amount of energy that the power plants can sell through bilateral contracts. For renewables sources, such as SH plants and WPPs, the FEC is based on the estimated long-term generation average.

A. Energy Short-Term Price: The Brazilian Dispatch Model

Brazil is an emerging economy with a huge territory (equivalent to the US continent plus half Alaska) and sharp demand growth (7% from 2009 to 2010, see [14]). Its energy production is highly hydro-based (85% in 2010) and spreads out through a complex cascade topology. Due to the vast number of interconnected basins, the Brazilian dispatch model is still cost-based and carried out in a centralized way by an independent system operator (ISO). It makes use of a Stochastic Dual Dynamic Programming (SDDP) methodology [4] to assess the optimal use of the water stored in the system reservoirs. In order to make the problem tractable, the system is divided into four equivalent nodal areas (north, south, southeast and northeast) and each area storage capacity, as well as the respective inflow patterns, is aggregated by equivalent reservoirs. The system dispatch tool simulates the system optimal operation throughout a long-term time horizon to assess the current expected value of the water opportunity cost and, consequently, the short-term prices. To do that, it takes into account the temporal and spatial correlation present in each of the four aggregated inflow patterns (see [15]) by means of a standard Monte Carlo simulation procedure.

The energy short-term price is a byproduct of a long-term dispatch model and relies on marginal operative costs (water values). Such marginal costs are obtained by means of the dual variables associated with power balance constraints in each of the four system areas. Moreover, its main characteristics are high volatility and negative correlation with the system storage. This occurs because the system was designed to supply the load under very adverse inflow conditions, which doesn’t occur frequently. Thus, in periods that the inflow presents its normal pattern, the demand is covered by hydro generation, leading to a very low marginal demand cost (zero in many periods). In contrast, when the system future reliability is in danger, the water value sharply increases and the marginal demand cost can reach very high values in a short period of time, like a week. Due to that, generation companies (Gencos) and consumers have incentives to negotiate through contracts.

III. A New Commercial Model for WPPs

In this section, a portfolio-based commercial model is proposed to mitigate the price-quantity risk faced by a WPP selling contracts in the FTE. The complementarity between generation profiles of wind farms and SHs in Brazil is well-known (see [12]). Therefore, the here-proposed commercial model taps into such complementarity to create a more stable combined generation pattern so that the need for purchasing energy in the short-term market is minimized.

A. Forward Contracts: The Price-Quantity Risk

In the FTE, contracts are typically standard forward agreements between two parts, buyer (consumer) and seller (generator), also known in Brazil as quantity contracts. The net revenue of a contracted Genco is composed of two terms: a fixed term, contract payment, and a variable term, revenue in the short-term market (spot). The following expression (1) illustrates the future (stochastic) cash flow of a Genco selling a forward contract as a function of the amount Q (in avgMW) being sold and its price P (\$/MWh). In this expression, unknown parameters are modeled by means of discrete random variables, which appear with an upper tilde. Their scenarios can be obtained by means of standard simulation procedures, e.g., a Monte Carlo simulation.

$$\tilde{R}_t(Q) = Ph_tQ + \tilde{G}_t\tilde{\pi}_t^G - h_tQ\tilde{\pi}_t^Q \quad \forall t \in H. \tag{1}$$

In (1), h_t is the number of hours in period t, $\tilde{G}_t$ is the generation (in MWh) of the Genco in period t, and $\tilde{\pi}_t^G/\tilde{\pi}_t^Q$ are, respectively, the short-term energy prices at the generator and contract nodal areas (in \$/MWh) in the same period t. Finally, H is the set of periods comprised in the contract time horizon.

If, in one hand, the first term of the expression (1) increases as the Genco contracts more; on the other hand, the third term decreases. This expression reveals a two-sided risk pattern: if a Genco contracts zero, it must sell all its generation in the short-term market, which is quite volatile, and if it contracts 100% of its FEC, the probability of a scenario with low generation and high price grows. The latter risk is the so-called price-quantity risk. Therefore, the amount of the FEC that should be sold by a Genco depends on its generation profile and should be optimized. This concept has been investigated in [1], [2], [6], and [7], all recent publications.

Fig. 1 depicts the observed generation profile of all Brazilian wind farms operating from 2007 to 2010 and the southeastern total inflow in the same period (on percentage basis of the respective long-term averages). It is possible to see that both sources are exposed to the price-quantity risk due to their seasonal and uncertain patterns. This is the main cause for WPPs to avoid the FTE. However, it is also notorious that both resources exhibit a complementary profile. Such synergy is measured and explored in the next subsections in order to mitigate the price-quantity risk.

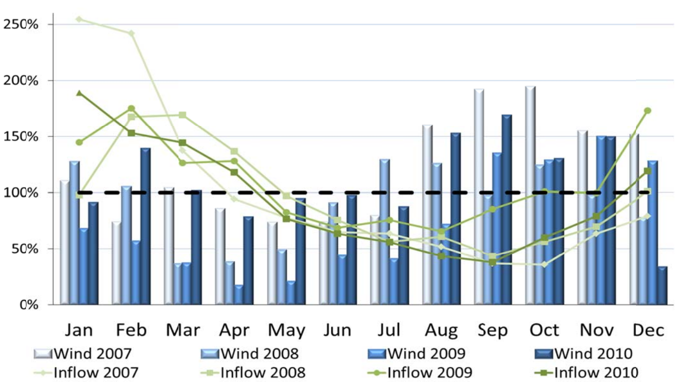

Fig. 1. Brazilian average generation profile of northeastern wind farms and southeastern hydro inflows (in percentage of the respective long-term averages) for 2007-2010 [14].

B. Risk Profile and the Value of a Trading Strategy

The core of the present work is to extract the value of the synergy between two complementary renewable sources when selling energy in the FTE. To do that, we need to specify the risk-profile that will be used throughout the paper. Moreover, we need to define a risk-averse measure of value, or certainty equivalent (CE), that assigns to each possible cash flow a monetary value. To define such measure, hereinafter referred to as ρ, we make use of a widely adopted coherent risk measure [8], namely Conditional Value-at-Risk (CVaR) [9]. Roughly speaking, such measure is the average of the $(1-\alpha)100\%$ worst scenarios, having α tipically ranging from 0.95 to 0.99, as shown in the next figure.

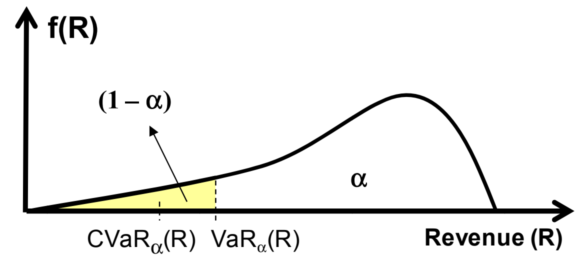

Fig. 2. Conditional Value-at-Risk of a general revenue probability mass function.

Hence, to assign a monetary-present value for a given stochastic multi-period cash flow $\{\tilde{R}_t\}_{t\in H}$, we adopt the following CVaR-based composite measure:

$$\rho\left(\{\tilde{R}_t\}_{t\in H}\right) = \sum_{t\in H} \frac{\lambda CVaR_\alpha\left(\tilde{R}_t\right) + (1-\lambda)\mathbb{E}\left(\tilde{R}_t\right)}{(1+K)^t}. \tag{2}$$

In (2), $\lambda \in [0,1]$ is a risk-aversion parameter and K is the Genco risk-free opportunity cost of money in percentage per period. Expression (2) can be seen as a (CE) for agents who choose it as an optimization objective function (see [9]). For $\lambda = 1$, ρ defines a strong risk-averse attitude. Decreasing λ until zero, we reach the case of a risk-neutral agent.

A Genco optimal trading strategy for a given forward contract, with known price P, is the optimal amount $(Q^*(P))$ that should be sold taking into account all the uncertainties that affect the contract cash flow, the Genco risk-profile, and its total amount of FEC F (in avgMW). The aforementioned definition is a particularization of the wilder concept of willing-to-supply (WS) curve (see [1][2][6]). An optimal trading strategy is a point in such curve. Finally, the value (v^*) of a given trading strategy is defined as the value, in terms of the Genco value function ρ, of the future cash flow generated by such strategy. It can be defined as follows:

$$v^*(F) = \max_{0\le Q\le F}\left\{\rho\left(\{\tilde{R}_t(Q)\}_{t\in H}\right)\right\}. \tag{3}$$

C. The Proposed Commercial Model

From a risk-averse point of view, it is reasonable to say that as long as the exposure to the price-quantity risk decreases, the optimal selling strategy for a given contract should increase. Therefore, the rationale of the proposed model is conceived from the viewpoint of a risk-averse WPP in order to let it take advantage from a contract opportunity in the FTE in a safer manner. This is done by reducing the seasonality in the generation profile through a portfolio composed of the WPP and a SH Genco. The idea is to attract a SH Genco partner to participate in the joint-selling strategy. In order to attract the SH Genco, the WPP, playing the role of central trading agent, provides a quota (%) of the joint-strategy cash flow to the SH so that it receives a surplus (defined as a percentage gain γ^{SH}) in comparison to the value of the cash flow it would receive in the market on her own. Then, the WPP receives the rest of the cash flow. Under this idea, the amount of hydro (FEC and generation) that should participate in the business to minimize the risk and maximize the WPP value should be optimized.

According to (3) and assuming the hypothesis of a contract market opportunity with price P, the value of an individual-trading strategy for a SH Genco can be denoted by: $v^{SH*}(F^{SH})$. Such value can be assessed by means of expression (1), replacing $\tilde{G}_t$ with the actual SH generation profile $\tilde{G}_t^{SH}$. By means of a convenient notation, the SH generation can be defined in terms of its FEC amount: $\tilde{G}_t^{SH}(F^{SH}) = \tilde{g}_t^{SH} F^{SH}$, where $\tilde{g}_t^{SH}$ is the normalized generation profile (per unit of FEC)[1]. It is not difficult to show that v^{SH*} is positive-homogeneous in the F^{SH} domain. Due to that, one can assess the value of a unitary FEC strategy for that contract and then multiply it by the total FEC (F^{SH}) to discover the actual value. This means that $v^{SH*}(F^{SH}) = F^{SH} v^{SH*}(1)$, or in short:

$$v^{SH*}(F^{SH}) = F^{SH} v^{SH*}. \tag{4}$$

To formulate the optimization problem that assesses the optimal SH partnership (amount of FEC and generation associated to it) together with the optimal joint-trading strategy, we first need to define the value of the WPP resulting cash flow. The joint strategy cash flow ($\tilde{R}_t^{JS}(F^{SH}, Q)$) is a function of two decision variables, namely, the amount of SH FEC (F^{SH}) that should participate in the model and the quantity that should be sold (Q). Such expression can be found by replacing, in (1), the generic short-term production revenue ($\tilde{G}_t \tilde{\pi}_t^G$) with the portfolio one ($\tilde{G}_t^{WPP} \tilde{\pi}_t^{WPP} + \tilde{G}_t^{SH}(F^{SH}) \tilde{\pi}_t^{SH}$, where $\tilde{\pi}_t^{WPP}$ and $\tilde{\pi}_t^{SH}$ are, respectively, the short-term prices of the areas where the WPP and the SH Genco are located). To achieve the WPP net cash flow we need to discount the payment for the SH Genco. Assuming that the SH Genco receives $\beta \cdot 100\%$ and the WPP, the remaining $(1-\beta) \cdot 100\%$ of the portfolio cash flow, the WPP net revenue in the joint strategy is as follows:

$$\tilde{R}_t^{WPP}(F^{SH}, Q) = \tilde{R}_t^{JS}(F^{SH}, Q)(1-\beta). \tag{5}$$

Applying the value function ρ to expression (5), due to its homogeneity property, one finds that

$$\rho\left(\{\tilde{R}_t^{WPP}(F^{SH}, Q)\}_{t\in H}\right) = \rho\left(\left\{\tilde{R}_t^{JS}(F^{SH}, Q)\right\}_{t\in H}\right) - \rho\left(\left\{\tilde{R}_t^{JS}(F^{SH}, Q)\right\}_{t\in H}\right)\beta. \tag{6}$$

Due to the same homogeneity property, the second term on the right-hand-side (RHS) of (6) can be rewritten as $\rho\left(\left\{\tilde{R}_t^{JS}(F^{SH}, Q)\beta\right\}_{t\in H}\right)$. This is exactly the value of the SH cash flow in the portfolio, which, by hypothesis, should meet the required amount of $(1+\gamma^{SH}) v^{SH*}(F^{SH})$. Thus, the joint-trading strategy can be found by maximizing the value of the cash flow allocated to the WPP:

$$V^{WPP*}(\gamma^{SH}) = \max_{Q, F^{SH}} \rho\left(\left\{\tilde{R}_t^{JS}(F^{SH}, Q)\right\}_{t\in H}\right) - F^{SH}(1+\gamma^{SH}) v^{*SH} \tag{7}$$

Subject to:

$$0 \le Q - F^{SH} \le F^{WPP} \tag{8}$$

$$0 \le F^{SH} \le UB^{SH}. \tag{9}$$

Assuming that uncertainties are discrete random variables, model (7)-(9) can be solved by means of commercial off-the-shelf linear programming solvers (see [10]). In (7)-(9), the objective function (7) represents the value of the cash flow earned by the WPP in the portfolio, constraint (8) requires that the joint-selling strategy is limited to the total FEC amount, and (9) limits the amount of SH FEC to an upper bound that represents the maximum FEC available to participate in that model. After the optimization process, the partition parameter β can be found as a function of the required gain (γ^{SH}):

$$\beta = \frac{(1+\gamma^{SH}) v^{SH*}(F^{SH*})}{\rho\left(\left\{\tilde{R}_t^{JS}(F^{SH*}, Q^*)\right\}_{t\in H}\right)}. \tag{10}$$

By definition, this is always a good business for the SH portion required to join the model (F^{SH*}). For the WPP, however, this is a good business whenever the value of the cash flow it receives is greater than the value of the cash flow it would receive selling energy out of the portfolio model. In the case study section we run sensitivity analysis on the SH gain to study the tradeoff between both generators.

IV. Renewable Resources Modeling

In the previous section we developed an optimization-based commercial model that takes into account the generation profiles of a WPP and a candidate SH partner to jointly sell energy in the FTE. In such model, the uncertainty parameters are: the SH and the wind power generation profiles, as well as the short-term energy prices. To run model (7)-(9), one needs scenarios and their associated probabilities, which generally are obtained by means of simulation procedures (see [1]).

Physical variables, such as the wind and inflows, generally exhibit a periodical and "well-behaved" pattern. In this sense, they are suitable for statistical modeling (see [12]) and can be easily simulated for long periods (more than one year in monthly basis) without violating their dynamics [15]. However, short-term prices dynamics are quite related with operative policies, especially in hydrothermal power systems, such as the Brazilian case, where this prices are set to be the system operation marginal costs. In this context, long-run dispatch models are known as the best simulation tool for short-term prices, preserving the long-run dynamics of this variable. As can be seen in Fig. 3, short-term prices are quite volatile and strongly dependent on the system operative decisions.

[1] Such parameterization lets us express the SH participation in terms of its FEC amount only.

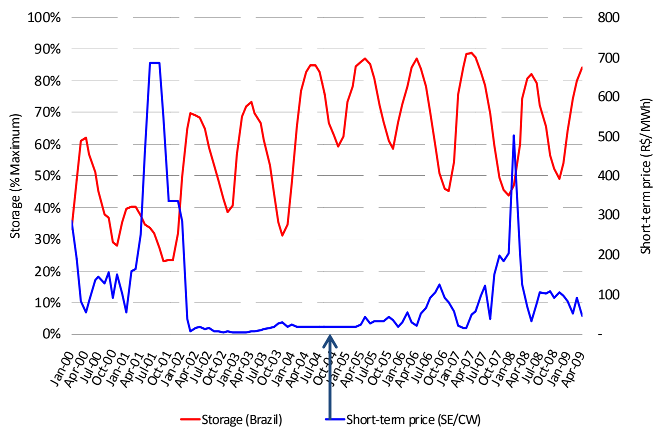

Fig. 3. Historical data of short-term prices and storage (% of the total capacity) at the southeastern area of Brazil [14].

Therefore, the objective of this section is to present a simulation methodology to generate scenarios for the renewable power plants considered in the present work, wind farms and SHs, consistently with a system dispatch simulation tool that provides scenarios of short-term prices [4]. Moreover, we consider that both the WPP and the SH are marginal to the system and that their generation profiles are not explicitly considered into the dispatch model uncertainties. This is the case of SHs and wind farms in Brazil.

In fact, the procedure to simulate the system dispatch and, therefore, the future marginal costs, is based on a primary simulation (set of scenarios) of the uncertainties considered in the dispatch tool (four equivalent reservoir inflows), hereinafter referred to as $\{\boldsymbol{x}_{ts}\}_{\substack{t\in H\\ s\in S}}$. Such primary-simulated time series feed the dispatch tool, which simulates the optimal operation of the system throughout the whole time horizon, here conveniently chosen to meet the contract time horizon (H). In this context, the simulated short-term prices scenarios can be seen as a function of the primary uncertainties scenarios as follows:

$$\{\boldsymbol{\pi}_{ts}\}_{\substack{t\in H\\ s\in S}} = DISPATCH\left(\{\boldsymbol{x}_{ts}\}_{\substack{t\in H\\ s\in S}}\right). \tag{11}$$

To simulate scenarios for the WPP and SH generations consistently with price scenarios simulated by the long-run dispatch model, we propose the following statistical model:

$$\widetilde{\boldsymbol{y}}_t = \boldsymbol{c} + \sum_{i=1}^{p} \boldsymbol{\phi}_i \widetilde{\boldsymbol{y}}_{t-i} + \sum_{j=1}^{q} \boldsymbol{\theta}_j \widetilde{\boldsymbol{x}}_{t-i} + \widetilde{\boldsymbol{a}}_t \tag{12}$$

$$\widetilde{\boldsymbol{a}}_t = \left(\sum_{i=1}^{p} \boldsymbol{A}_i d_{it}\right) \widetilde{\boldsymbol{\varepsilon}}_t \tag{13}$$

$$\widetilde{\boldsymbol{\varepsilon}}_t \sim N\left(\begin{bmatrix}0\\0\end{bmatrix}, \begin{bmatrix}1 & r\\ r & 1\end{bmatrix}\right) \text{ and } \boldsymbol{A}_i = \begin{bmatrix}\sigma_i^{WPP} & 0\\ 0 & \sigma_i^{SH}\end{bmatrix}. \tag{14}$$

Where $\widetilde{\boldsymbol{y}}_t = \left[\tilde{G}_t^{WPP}, \tilde{g}_t^{SH}\right]^T$, p is the number of autoregressive lags considered in the model (in the present work we have set it to 12, since time granularity is monthly based), and q represents the explicative (conditional) variable lags taken into account in the model. Expression (12) is a standard vector autoregressive with explicative variable formula [11]. In such expression, the dispatch model input random variables play the role of explicative variables, providing the link between the dispatch output variables (short-term prices) and the renewable generation. Therefore, $\widetilde{\boldsymbol{y}}_t$ can be seen as a function of $\{\widetilde{\boldsymbol{x}}_{t-j}\}_{j=1}^{q}$, which means that for each simulated dispatch scenario s, the renewable model adjusts itself and provide scenarios that are statistically dependent on the pair $(\{\boldsymbol{\pi}_{ts}\}_{t\in H}, \{\boldsymbol{x}_{ts}\}_{t\in H})$. Expression (13) imposes a variance law to the model, where d_{it} is an indicator (0/1) variable, which values one if period t refers to month i and values zero otherwise. Hence, according to (13), $\widetilde{\boldsymbol{y}}_t$ has different variances for each month. Additionally, r is the residual covariance and $\sigma_i^{(.)}$ is the residual variance for each generation model (WPP and SH).

Finally, the simulation methodology to produce the set of dependent scenarios of renewable generation and short-term prices $\{\{\boldsymbol{\pi}_{ts}\}_{t\in H}, \{\boldsymbol{y}_{ts}\}_{t\in H}\}_{s\in S}$ is divided into the following three steps:

1. Adjust model (12)-(13) using historical data of the WPP and SH generation profiles and the historical data of the dispatch model input variables.
2. Run a system dispatch simulation procedure (such as [5]). This will provide a set of scenarios of paired input-output dispatch variables:
$$\{\{\boldsymbol{x}_{ts}\}_{t\in H}, \{\boldsymbol{\pi}_{ts}\}_{t\in H}\}_{s\in S}.$$
3. Use the dispatch input scenarios to produce paired generation scenarios for the renewables:
$$\{\{\boldsymbol{x}_{ts}\}_{t\in H}, \{\boldsymbol{\pi}_{ts}\}_{t\in H}, \{\boldsymbol{y}_{ts}\}_{t\in H}\}_{s\in S}.$$

In step 3, the first variable can be dropped and the last two can be used in the optimization problem (7)-(9). The above simulation procedure is depicted in Fig. 4:

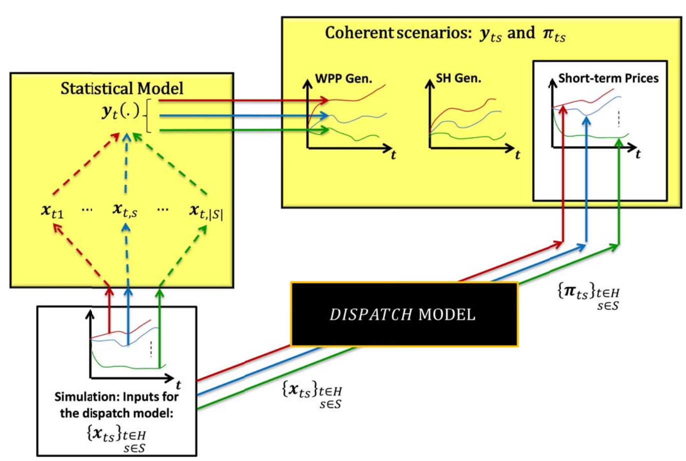

Fig. 4. Simulation procedure to produce dependent scenarios of renewable generation and short-term prices.

V. Case Study

In the Brazilian power system, wind power generation is a recent technology, and long-term wind measurements at 80 to 100 meters, relevant for wind farm economic assessments, are unavailable or kept as strategic private information by WPPs. On the hydro side, the reciprocal is not true. Due to the Brazilian power system characteristics, hydrological patterns have been often studied and the main basin historical data is available [13]. In this context, the present case study makes use of synthetic generation historical data for a 30 MW wind farm on the northeastern part of Brazil, with a long-run average generation (FEC) equal to 11.5 avgMW. As a SH partner candidate, we have considered a fictitious 30 MW SH power plant at the Paraibuna river, in the southeastern part of Brazil, with a long-run average generation (FEC) equal to 18.4 avgMW. The next figures depict such data:

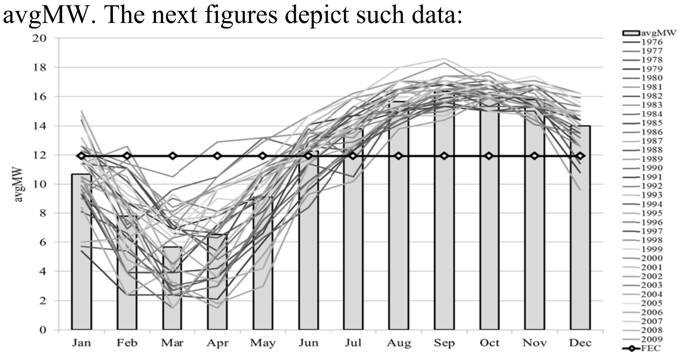

Fig. 5. Synthetic historical data generated for a 30 MW wind farm at the northeastern area of Brazil.

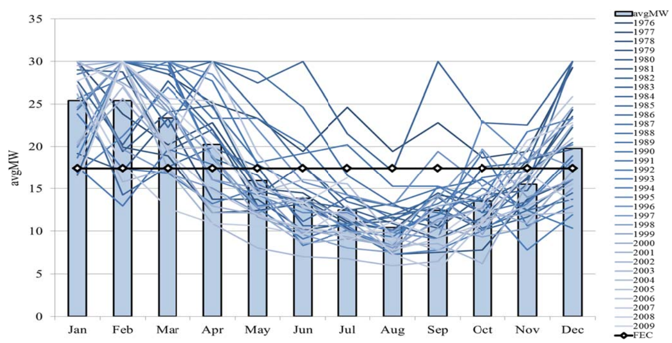

Fig. 6. Synthetic historical data generated for a 30 MW small hydro plant at the southeastern area of Brazil.

The goal of this case study is to show that the proposed commercial model (7)-(9) provides relevant benefits for both the SH and the WPP, with realistic data from the Brazilian power system. To do that, we apply the three-step methodology developed in the previous section based on a system simulation carried out by the ISO on march 2011 [14]. In the present case study, we assume a market opportunity demand in the northeastern nodal area for a one-year (2014) contract of 20 avgMW[2] for 100 R$/MWh. For the sake of simplicity, we set the money discount factor (K) to zero. Moreover, the risk-aversion parameters λ and α were respectively set to 1 and 0.95, characterizing a strong risk-aversion. The average and 90%-confidence interval (CI) for the simulated variables are provided in Fig. 7. In Fig. 8, the same statistics are provided for the optimal portfolio.

[2] If the market opportunity is limited, it can be easily incorporated into the model as an upper bound constraint for Q.

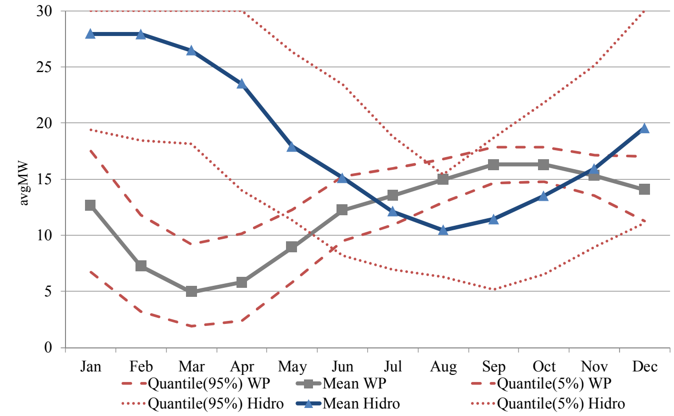

Fig. 7. Average and 90%-CI for the renewable generation profiles (data for 2014, in monthly basis).

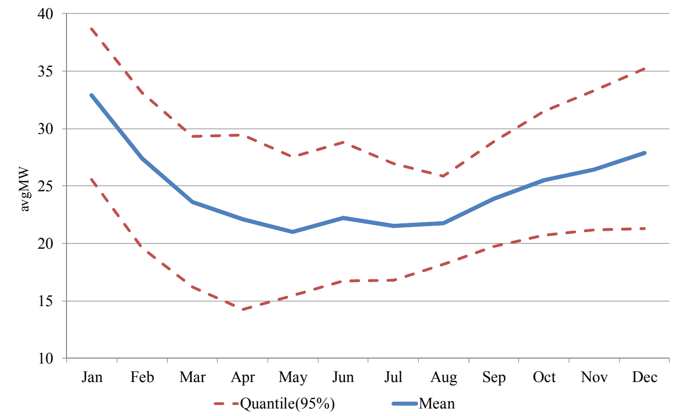

Fig. 8. Average and 90%-CI for the optimal portfolio generation profile (data for 2014, in monthly basis).

A. Experimental Results for a 10% SH Gain

In a first analysis, we arbitrary set the required SH gain to $\gamma^{SH} = 0.1$. The optimal joint strategy is to supply 19 avgMW backed up by 24.6 avgMW of the total FEC. Such portfolio amount is composed of the WPP FEC (11.5 avgMW) and the invited SH partner, which in the optimal solution participates with 13.1 avgMW. The following tables summarize the main optimization results:

TABLE I
TRADING STRATEGY RESULTS (QUANTITIES)

Agent	Q^* (avgMW)	FEC (F) (avgMW)	Q^*/F (%)
Only SH	9.9	18.4*	54.0%
Only WPP	10.2	11.5	88.7%
Portfolio	19.0	24.6**	76.9%

* $F^{SH} = UB^{SH}$.
**Total FEC after optimization = $F^{WPP} + F^{SH*}$

TABLE II
FINANCIAL RESULTS

Agent	Average (MM R$)	$CVaR_{0.95}$
Only WPP (v^{WPP*})	9.98	8.16
WPP in the Portfolio (V^{WPP*})	11.88	9.69
Absolute Gain	1.90	1.53

From Table II, we can assess the relative gain of the WPP: $\gamma^{WPP} = 18.7\%$. The effect of such gain in the annual revenue accumulated probability function can be seen in Fig. 9. This second table provides us with the following practical conclusions:

(i) the WPP is able to mitigate the price-quantity risk in the FTE under the proposed methodology, increasing the value of its optimal selling strategy by 18.7% and

(ii) if we compare the average of the 5% worst revenue scenarios (the $CVaR_{95\%}$ column in Table II) with a risk-free reference opportunity at the same price, where the consumer assumes the whole production risk and rents the wind farm for a fixed (deterministic) payment of $F^{WPP} \cdot P \cdot 8760 =$ 10.1 MM R\$, we will find that, under the proposed commercial model, the WPP CE is only 4.1% worse than such reference, while out of the portfolio, it is 19.3% worse.

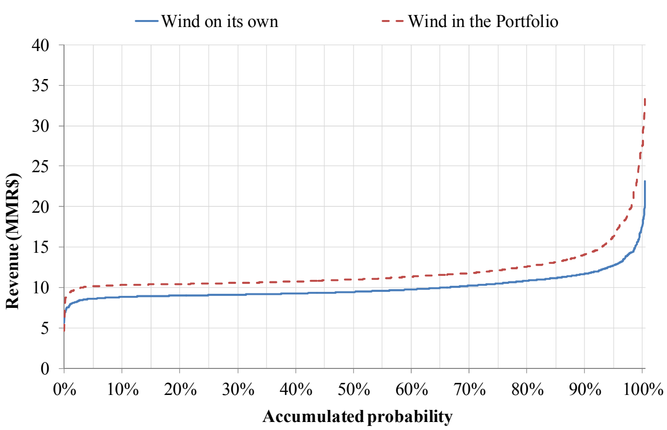

Fig. 9. Annual revenue accumulated probability function for the WPP in and out of the portfolio.

B. *Sensitivity Analysis on the SH Gain*

By definition, the proposed joint-trading strategy is always a good business for the SH portion required to join the model (F^{SH*}). For the WPP, however, this is a good business whenever the value of the cash flow it receives is greater than the value of the cash flow it would receive selling energy out of the portfolio model. Since the WPP is a constant in the model, such value can be assessed directly from (3) as v^{WPP*}. Moreover, one can argue that such business is fair whenever the gain provided to the SH Genco is equivalent (in percentage basis) to the WPP gain, γ^{WPP}. This is the same as $\gamma^{WPP} = \gamma^{SH}$, which is equivalent to a proportional nucleolus share in a cooperative game setting (see [7]). Needless to say, in the present model, the WPP does not need to provide a fair partition. It only has to provide a gain so that it guarantees the SH partnership. However, for a WPP running this model, it is worth to have this value in mind as a reference. Overcoming this reference, one can say that such model benefits more the invited partner, the SH Genco, than its own owner, the WPP. The reference gain provided to the SH can be numerically assessed by running model (7)-(9) for different values of γ^{SH}.

The WPP gain in the joint-strategy is a function of the gain required by the SH partner. As argued before, it is worth to study such dependence when negotiating with candidate partners. In this sense, model (7)-(9) was run several times, for different values of γ^{SH}, and the resultant WPP gain (γ^{WPP}) and the amount of SH FEC required by the optimal joint strategy (F^{SH*}) were calculated. Fig. 10 shows those values.

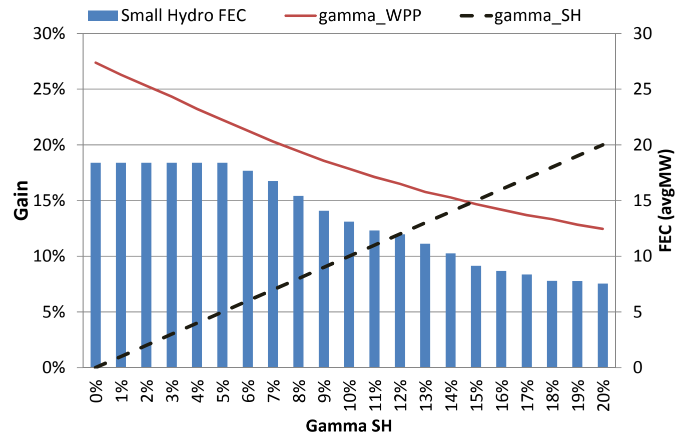

Fig. 10. Optimal results as a function of the partner required gain $\boldsymbol{\gamma^{SH}}$.

This figure illustrates the dependence of the WPP on its hydro partner. It is worth mentioning that when the SH required gain overcomes 15%, the WPP gain drops to values below the SH gain. In this sense, one finds that, according to the last paragraph of section III.C., 15% represents the reference point for which the SH and WPP gain are equal. Furthermore, as expected, it is possible to see that as long as the SH required gain increases, the optimal required amount of hydro FEC decreases.

VI. Conclusions

This paper presents a new and practical commercial model to foster the penetration of a WPP into the Brazilian FTE. The main idea behind such model is to mitigate the price-quantity risk of a WPP by means of a portfolio with a SH Genco. To assess the benefits of such approach, a statistical model was proposed. It is capable to produce generation scenarios for the wind and hydro power plants consistently with short-term price scenarios simulated by a hydrothermal dispatch model. Results corroborate the applicability of the proposed methodology and its ability to enhance the WPP wealth while still providing a value increase for the SH partner. The main results show that our model is capable to increase the value of a WPP trading strategy by 18.7%, which reduces the distance between the value of a trading strategy in the FTE and a risk-free reference revenue from 19.3% to 4.1%. The proposed methodology is currently being tested in the Brazilian power market by trading companies and Gencos.

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VIII. Biographies

Alexandre Street (S'06–M'10) holds an M.Sc. and a D.Sc. in Electrical Engineering (Operations Research) from the Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil.

From August 2006 to March 2007 he was a visiting researcher at the Universidad de Castilla-La Mancha, Ciudad Real, Spain. From 2003 to 2007 he participated in several projects related to strategic bidding in the Brazilian energy auctions and market regulation at the Power System Research Consulting (PSR), Rio de Janeiro, Brazil. In the beginning of 2008 he joined PUC-Rio to teach Optimization in the Electrical Engineering Department as an Assistant Professor. His research interests include: strategic bidding in energy contract auctions, energy markets regulation, optimization methods, and decision making under uncertainty.

Delberis A. Lima received the B.Sc. degree in electrical engineering and the M.Sc. degree from Universidade Estadual Paulista (UNESP) Júlio de Mesquita Filho, Ilha Solteira, São Paulo, Brasil, in 2000 and 2003, respectively. He was a Research Visitor at the Universidad de Castilla—La Mancha, Ciudad Real, Spain, in 2005. He is currently teaching at Pontifical Catholic University of Rio de Janeiro (PUC-Rio). His research interests include power systems planning, operations and economics, and electricity markets.

Álvaro Veiga has a PhD degree in Telecommunications from ENST-Paris. He is an Associate Professor at the Department of Electrical Engineering of PUC-Rio. He participates in research and consulting projects on stochastic modeling for finance, risk analysis, and stochastic optimization.

Bruno Fânzeres has a B.Sc. in Electrical Engineering from PUC-Rio. He is currently pursuing a M.Sc. degree in Electrical Engineering at the same University and his research interests include: operations, planning, and power system economics.

Lucas Freire received his B.Sc. degree in Electrical Engineering at Pontifical Catholic University of Rio de Janeiro in 2010. He is currently a student of MSc. in Electrical Engineering at the same University. His areas of interest are renewable energy, energy markets, and optimization theory.

Bianca Amaral received her M.Sc. degree in Electrical Engineering at Pontifical Catholic University of Rio de Janeiro in 2011. She is currently a student of D.Sc. in Electrical Engineering at the same University. Her areas of interest are renewable energy and statistical modeling.

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