On the Regulatory and Economic Incentives for Renewable Hybrid Power Plants in Brazil

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Abstract

The complementarity between renewable generation profiles has been widely explored in the literature. Notwithstanding, complex interactions between regulatory and economic frameworks add interesting challenges and opportunities for hybrid power plant investors, regulators, and planners. Focusing on the Brazilian power market, we study the alignment of incentives between the economically-optimized strategy of hybrid power plant investors and the efficient utilization of the transmission resources. To do that, we propose a decision model that co-optimizes the risk-adjusted strategy of a hybrid power plant owner comprising i) the forward-market involvement, ii) the contracted amount of network access, and iii) the share of renewable sources composing the hybrid power plant. We also propose adjusting the current regulatory framework to consider a unified calculation for the Firm Energy Certificates of non-controllable renewable power plants, including hybrid units. Based on that, we ensure a non-discriminatory regulatory framework for renewables acknowledging the diversity of generation profiles that hybrid units may have due to their optimal hybridization shares and network-access contracting strategies. A case study using realistic data from the northeastern region of the Brazilian power system showcases strong economic incentives for hybridization with reduced transmission resource utilization.

Keywords: Firm energy certificate, forward contracts, hybrid power plants, market design, transmission network access, renewable generation, risk management, wind and solar complementarity.

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1. Nomenclature

This section briefly introduces the nomenclature of the mathematical terms we use throughout the text. The section can be used for reference and clarification while reading the paper. In each subsection, we provide the logic of the nomenclature to facilitate the reading.

1.1. Sets and Indices

Sets, except for the typical sample set, Ω, are presented in mathematical calligraphy style as follows:

$\mathcal{M}$	Set of months of the optimization horizon. We use m to denote its elements.
$\mathcal{H}, \mathcal{H}_m$	Set of hours in the historical data (past) and subset of hours of a given month m of the year, respectively.
$\mathcal{T}, \mathcal{T}_m$	Set of hours defining the optimization horizon and subset of hours of a given month m of the year. We use $t \in \mathcal{T}$ to denote the hours in the study horizon (future).
Ω	Set of scenarios (sample space). We use $\omega \in \Omega$ to denote a given scenario.

1.2. Random variables

Random variables, which are functions from the sample set onto the real line, are presented with an upper tilde as follows:

$\tilde{\pi}_t$	Spot price of a given hour $t \in \mathcal{T}$ (\$/MWh). We assume $\pi_{t,\omega}$ as its realization for a given scenario $\omega \in \Omega$.
$\tilde{g}^S_t$	Solar available generation of a given hour t (MWh). We assume $g^S_{t,\omega}$ as its realization for a given scenario $\omega \in \Omega$.
$\tilde{g}^W_t$	Wind available power generation of a given hour $t \in \mathcal{T}$ (MWh). We assume $g^W_{t,\omega}$ as its realization for a given scenario $\omega \in \Omega$.

1.3. Constants and parameters

Constants do not have a specific style. In this work, the following constants are used in the mathematical models:

c	Network-access contract tariff (\$/MW).
C^S	Investment expendure CAPEX on solar installed capacity (\$/MW).
C^W	Investment expendure CAPEX on wind intalled capacity (\$/MW).

p Forward contract price (\$/MWh).

α CVaR confidence level (risk-aversion parameter).

λ CVaR weight (risk-aversion parameter).

G_t^S Historical generation data of the solar generator for hour $t \in \mathcal{H}$ (MWh).

G_t^W Historical generation data of the wind generator for hour $t \in \mathcal{H}$ (MWh).

$\mathbf{G}$ Generic vector stacking the whole historical generation data (MWh). In the text, we consider variants of it for solar generation data ($\mathbf{G}^S$), wind generation data ($\mathbf{G}^W$), and the generation data of the hybrid unit ($\mathbf{G}^H$).

1.4. Decision Variables

Decision variables do not have a specific style. In this work, the following variables are defined in the proposed co-optimization model for hybrid power plants decision making:

M Network-access contract quantity amount (MW).

Q Forward contract quantity amount (MWh).

x Percentage of solar generation on installed capacity composing the 1–MW hybrid power plant.

$\hat{g}_{t,\omega}^H, \hat{G}_t^H$ Auxiliary decision variables used to represent the truncated generation (after curtailment) for both simulated and historical data, respectively.

1.5. Functions

Functions are presented with $(\cdot)$ to showcase their dependency on other variables. In this work, we use the following functions:

$\mathbb{F}(\mathbf{G}, M)$ Firm energy certificate (FEC), in average MW (avgMW), of a non-controllable renewable generator as a function of $\mathbf{G}$ and M.

$G_t^H(x)$ Historical available generation data of the hybrid power plant composed of x–MW of solar and $(1-x)$–MW of wind for an hour $t \in \mathcal{H}$.

$\hat{\tilde{g}}_t^H(x, M)$ Generation output truncated on M for the hybrid power plant composed of x–MW of solar and $(1-x)$–MW of wind for an hour $t \in \mathcal{T}$, defined as $\hat{\tilde{g}}_t^H = \min\{x\tilde{g}_t^S + (1-x)\tilde{g}_t^W, M\}$. We assume $\hat{g}_{t,\omega}^H$ as its realization for a given scenario $\omega \in \Omega$.

2. Introduction

Brazil has one of the world's most renewable generation fleets [1]. However, it is a latecomer in contrast to the US and EU in the installation of wind, solar, and hybrid generation. Hybrid generation units have shown to be an effective way to reduce the intermittence of non-controllable renewable generation (see [2]) and, consequently, have the potential to increase renewables' firm energy production. For instance, the complementarity between solar and wind generation has been studied in US [3], Europe [4], and Brazil [5]. In the energy transition context, renewable sources, not only in Brazil, have been demanding a great effort from both the academy and industry sides to address the increasing grid congestion and detrimental effects on reliability due to intermittence on the operational, planning, and market sides (see [6], and [7] for further reference).

Aiming to provide further evidence about the value of studying and exploring the complementarity between wind and solar worldwide, we briefly review recent work on the subject. More specifically, [3] provides detailed descriptive analyses of historical data for different sites in Texas, US, and studies their firm capacity. Results indicate relevant intra-state complementarity indices, with the West Texas wind exhibiting the most relevant complementarity with the solar generation profile. In [4], statistical analyses also identify local complementarities in many European regions. The study finds that the complementarity varies for regions and months of the year, and identifies the summer with the most regular complementary pattern from year to year. More recently, in [8], the effect of hybridization and nearby transmission needs are investigated in different US regions, demonstrating the interactions between transmission policies and the economic incentives for hybrid configurations.

Returning to the Brazilian scenario, in [9], an interesting technical analysis of the long-term supply capacity of potential hybridization between local wind and solar generation in the Brazilian Northeastern region. The study is carried out based on reanalysis data and local measurements to create representative data from the analyzed region and focused on finding the best shares of complementary wind and solar generation to meet the local demand profile (annually, monthly, and hourly). The best spot identified was Açurua, Bahia State, Brazil. Percentages ranging from 20% to 31% for the solar are found when minimizing the mean absolute error between the resulting hybrid generation and historical load. In [5], the complementarity between wind and solar generation is analyzed, and relevant negative correlation values are found in the Northeastern region of Brazil. The firm supply capacity of a wind and solar hybrid plant operating with a dedicated battery is analyzed with relevant historical data from the Brazilian power system. Results show that a 40% solar and 60% wind share is the mix that minimizes the load not served. Results using historical data and a curtailment minimization criterion also demonstrate a potential reduction in transmission infrastructure needs due to the complementarity.

The relevance of the previously reported studies notwithstanding, the commercial value of the resulting generation profile and its interaction with the forward and spot market strategies, as well as with the cost of transmission access, were not taken into account within a risk-averse decision-making framework. However, as per [8], it is important to analyze hybrid power plants within their specific regulatory and market contexts, as they define much of the possible revenue outcomes and, thereby, have a major influence on the generation companies' decision-making process.

The core of the Brazilian power market and its regulatory system is based on long-term forward contracts and firm energy certificates (FEC). While the former allows for a more stable net revenue (see [10]), the latter assigns to each unit a regulatory stamp regarding its capability to supply energy under adverse conditions (see [11]) for a detailed description of the concept and allocation methods). Based on these two instruments, as described in [10], a link between demand growth and supply adequacy is created by a regulatory system that requires: 1) loads need to be 100% contracted, and 2) every contract needs to be 100% covered by physical generation capacity, which in Brazil is certified by FECs. So, in the current regulatory framework in Brazil, no generation can sell more than its FEC amount. However, renewable generators face an additional risk due to their uncertain generation. The so-called price-and-quantity risk poses a severe risk when renewables fall short in generation during high spot price periods (see [12] and [13] for relevant publications on the subject). Thus, for contracted renewables in Brazil, more consistent (or more firm) generation is crucial to attaining profitable contract positions by mitigating the price-and-quantity risk. This presents a significant additional incentive for hybridization in forward contract-oriented markets.

Within this context, the advantages of combining renewables in a portfolio of complementary sources to back long-term forward contract sales have been demonstrated in several papers for the Brazilian power system. In [12], for the first time, complementary renewable sources, namely, a biomass unit and run-of-riven small hydro, were combined through a risk-constrained optimized portfolio to mitigate the price-and-quantity risk and back a forward contract sell in the free trading forward market. In [14], the complementarity and risk-mitigation benefit of a large set of renewables coordinated in a single renewable pool to sell contracts in the market with lower risk was studied. More specifically, an allocation rule to distribute the shares among the renewables participating in the pool was devised based on the nucleolus of a stochastic cooperative game. In [15], the complementarity of renewables was also studied in the presence of different markets and contract formats. Finally, more recently in [13], forward contracts and call options were used to mitigate the price-and-quantity risk in complementary portfolios of renewables considering ambiguity on the probability distributions.

Based on previously reported work, the complementarity of renewables has been demonstrated to be an effective hedging strategy for renewables in the Brazilian electricity forward market, paving the way for the commercialization of large shares of these sources in Brazil in the last decade. Nevertheless, as per [16], the significant and unsynchronized integration of wind power into the northeastern area of Brazil, disregarding appropriated transmission incentives for complementarity, has led to a significant increment in transmission needs.

Similarly to the Transmission Entry Capacity in the UK (see [17], [18], and [19]), in Brazil, all generators and consumers connected to the transmission system must pay for its utilization, which is managed through a network access contract (NAC). This contract also grants the right to inject or extract power from the transmission system. In the case of generators, they are charged monthly for the total NAC, as well as for any injections surpassing it (within a 15-minute time window). However, in contrast to the previously reported Transmission Entry Capacity case, the current Brazilian regulatory design imposes generators to contract their total installed capacity. Thus, within the Brazilian regulatory framework, NACs are used for three purposes in Brazil: 1) to share transmission costs among generation and consumers (on a 50/50 basis) while signalizing through locational tariffs generation expansion needs [20], 2) to evaluate the system's ability to integrate new units (and plan reinforcements if needed), and 3) to enforce an economically rational utilization of the existing and new transmission resources.[2]

Regarding the latter (purpose number 3), the Brazilian regulatory framework was recently updated to align and potentialize the hybridization benefits in reducing transmission needs with the economic incentives for renewable generation investors (we refer to [24] and [25]). More specifically, the maximum power of a hybrid power plant composed of complementary renewable resources is expected to only occur with a low probability. Based on that, according to the regulatory updates, hybrid power plants can voluntarily reduce NAC amounts in relation to their total installed capacity, thereby reducing their transmission payments and utilization demand.

The challenge, however, is the following: while reducing the NAC directly reduces the generator's transmission payments and utilization, it also increases the probability of self-curtailment actions to avoid violation penalties, as provided for in the NAC clauses, which should reduce spot market revenues. So, besides the annualized capital expenditures (CAPEX) and generation profile of each source, the economic incentives for investing in hybrid renewable generation in Brazil rely on two key and oppositive forces, namely, 1) the risk-adjusted maximization of forward and spot market revenues and 2) the minimization of network-access contract payments. In this context, the regulatory update has transferred to generation investors the responsibility and the benefits of finding the most economical composition of renewable generation profiles to balance their energy revenues and transmission utilization. As wind and solar generation profiles exhibit relevant complementaries in the northeast of

[2]For the interested reader, we refer to [21] and [22] for a detailed discussion on the network access charges in Brazil for the demand side, to [23] for a report on the inadequacies of the Transmission Entry Capacity for variable and distributed generation in the UK, to [18] for the UK's evolving regulatory landscape and market structures for network access, and to [19] for different methodologies to issue a robust maximum Entry Capacity.

Brazil, a rational risk-averse economic agent is expected to reduce its transmission access amounts. This is a relevant research topic this paper aims to address.

Notwithstanding, although the complementarity between renewable sources has been demonstrated to be beneficial for both the renewable generation owners and system sides, the effectiveness of hybridization, on the other hand, mainly relies on the interactions of the regulatory framework, market instruments, and the risk-attitude of generation companies in terms of economic incentives. Therefore, the study and development of new tools for generation risk management and market-integrated strategic decision-making are key for analyzing the development of hybrid power plants and their potential benefits for the system. For instance, in the Brazilian case, the study of the interactions between the forward market involvement, the network-access contracting strategy, and the shares of sources composing the hybrid unit constitute an additional relevant thrust for the sustainable development of renewables. Unfortunately, none of the previously reported work addresses these relevant aspects.

Besides the economic incentives of combining complementary resources, the regulatory framework for hybrid generation in Brazil, as well as in other developing countries, is still under development (see the preliminary discussions in [24], [26] and [27]). For instance, the Brazilian concept of FEC for non-controllable renewable generation (wind, solar, biomass, and small run-of-the-river hydros) lacks uniformity. Each renewable source in this country has a different FEC calculation methodology, creating a non-isonomic treatment among sources. Additionally, in the case of hybrid units, the challenge is that reducing the NAC potentially changes the final generation profile. Thus, to coherently accommodate the previously explained benefits of renewable hybrid power plants into the Brazil regulatory framework in a non-discriminatory way, it is key that 1) non-controllable renewable sources, including hybrid units, have a source-agnostic FEC calculation and 2) it can capture the effect of reducing the NAC. However, none of the previously reported work deals with the impacts on the FECs of hybrid power plants arising from their economic strategies. Hence, in this paper, we also propose that non-controllable renewables and hybrid plants should have a unified and isonomic regulatory FEC calculation methodology based on the total generation output adjusted by the NAC limit. In this format, in both planning and economic studies, the FEC of a hybrid unit can reflect its energetic contribution to the system according to an economically calibrated utilization of the transmission resources.

2.1. Objective and contributions summary

Based on the identified literature gaps, the objectives of this paper are twofold: 1) to derive and study the risk-adjusted market and development strategy of hybrid power plant owners in the Brazillian electricity market considering the co-optimized interactions of the forward-market involvement, the contracted amount of network access, and the shares of renewable sources, and 2) to propose a new unified and non-discriminatory FEC calculation for non-controllable renewables and hybrid units.

To achieve the objectives of this work, we contribute to the state-of-the-art literature and current industry practices as follows:

1. We provide a new economic analysis tool for (wind and solar) hybrid power plants to quantify and co-optimize their commercial and development strategies considering the investor's risk aversion and correlated generation and price uncertainties. Based on representative data from the Northeastern region of Brazil, we demonstrate the benefits of an integrated co-optimized solution comprising the plant's forward-market involvement, the amount of network access that should be contracted, and the share of each renewable source composing the hybrid plant. Our results also showcase that the individual economic incentives associated with the proposed strategy are economically aligned with the transmission system's interests, resulting in a reduced need for additional transmission capacity to integrate co-optimized hybrid plants. We also envision that the proposed analytics tool and results can be used in practice by generation companies and system entities (planner, operator, and regulator) in many different applications, e.g., generation expansion, market equilibrium, and transmission planning.

2. The definition of a unified FEC calculation for non-controllable renewable units and hybrid power plants that aligns i) the economic incentives found for generation companies to explore complementary renewable generation profiles with ii) the reduction of new transmission reinforcement needs to integrate the new renewable fleet. We demonstrate through a theorem that the proposed framework encourages the system's expansion through complementary renewable energy resources by offering a greater or equal FEC for the same amount of transmission access. Therefore, the proposed FEC methodology acknowledges the current regulatory intention to certify the average generation capacity of renewables without disregarding relevant existing synergies and gives a step further in the direction of a more coherent, non-discriminatory, and incentive-based regulatory framework for power systems with large shares of renewable generation.

The remainder of this paper is organized as follows. In Section III, we describe the general data framework used in this work. In Section IV, we describe the current regulatory framework in Brazil regarding NAC and FEC, whereas in Section V, we present and study the proposed unified FEC concept for non-controllable renewables and hybrid power plants. In Section VI, we introduce the network-access and forward contract co-optimization model, and in Section VII, we present two case studies to illustrate its usage and benefits with realistic data from the Brazilian power system. Finally, in Section VIII, we summarize the main conclusions and highlight interesting future extensions of this work.

3. Data framework and uncertainty representation

In this work, two temporal horizons are considered, namely, 1) the historical horizon, which is characterized by the set of hours in the past ($\mathcal{H}$) for which generation data is assumed available, and 2) the future horizon, characterized by the set of hours ($\mathcal{T}$) for which the both the NAC and forward contract amounts are optimized. While the FEC is defined using historical generation availability data ($\{G_t^S, G_t^W\}_{t\in\mathcal{H}}$), thereby defined based on $\mathcal{H}$, the stochastic revenue of the hybrid power plant devising its optimal joint contracting strategy is defined based on simulated scenarios of the future generation availability and spot prices ($\{g_{t,\omega}^S, g_{t,\omega}^W, \pi_{t,\omega}\}_{t\in\mathcal{T},\omega\in\Omega}$) within the contracting horizon $\mathcal{T}$. We refer the reader to the nomenclature section for further details.

It is relevant to mention that the historical generation availability, defined as the generation given the resource availability disregarding curtailments, might not be observable in some cases. Additionally, new projects with no historical generation data or existing units subject to systematic curtailments constitute relevant examples. Many works have dealt with this challenge, and relevant methodologies have been developed to generate or extend historical data (we refer to [28] and [9]).

In this work, the generation availability is assumed as an input. It means that the proposed model and FEC methodology are both agnostic to the methods used to synthetically extend or generate representative data. In this context, different methods to treat, extend, or even generate historical data sets can be used according to the application (investment evaluation of new units, transmission and generation expansion planning, or specific studies on commercialization strategies). In the following subsections, we provide more details on the methods used to generate representative historical data sets and simulated scenarios for the future generation availability of a realistic hybrid unit in the Northeastern region of Brazil. For reproducibility purposes, the complete data set (historical and simulated data) is publicly available in [29].

3.1. Historical data

To derive realistic studies with representative data from the Northeastern region of the Brazilian power system, we build an unconstrained generation data set (free of curtailment actions) of wind and solar power generation in the same generation site using real data from the Bahia state. To do that, we use reanalysis data and applied a bias correction based on real measurements of generating units of the same region (Bahia state) following the methodology implemented in the Time Series Lab software, from PSR-Consulting [30], available at [31]. Figure 1 depicts the average hourly generation profiles, with data from 2008 to 2017 and a negative correlation approximately equal to -0.4. Interestingly, the correlation coefficients calculated with the data from 01/2008 to 12/2017 between the wind power generation profile used in this paper and the wind power generation measurements from different units in the Northeastern regions of Bahia ranges between 0.8 and 0.9, corroborating the representativeness of the data set used in this work.

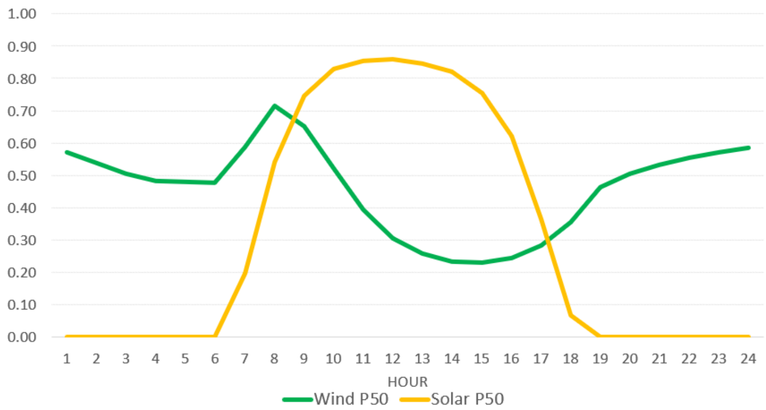

Figure 1: Wind and Solar generation profile, for each hour of the day, 2008-2017.

3.2. Scenarios for the future generation availability

The uncertainty of the future generation of the hybrid power plant and spot prices is modeled through a non-parametric Bayesian network model. Thus, the joint empirical distributions of spot price and renewable generation are characterized through a sample of scenarios generated through Monte Carlo simulation [32]. To account for the cross-dependency between renewable generation and spot prices, we simulated coupled scenarios for the three-dimensional time series comprising the spot prices, wind generation, and solar generation for every hour in $\mathcal{T}$. To do that, we used the commercial hydrothermal dispatch model SDDP (from PSR Consulting) to simulate Brazilian spot prices based on the scenarios for the main renewable spots of the Brazilian system, including the solar and wind generation studied in this paper. We selected 2025 as the target year for the contracting horizon $\mathcal{T}$. Finally, the simulated scenarios, represented by the sample-space set Ω, will be used as inputs in the risk-adjusted two-stage stochastic model presented in Section VI.

4. Regulatory framework

4.1. Network-access contract (NAC)

The network cost is shared through consumers and generators (50-50 %) connected to the Brazilian high-voltage transmission network (230+ kV). In the general case, as per the current Brazilian regulation, a minimum amount of NAC M must be equal to the total installed capacity of the power plant, assuming that at least in one 15-minute interval, the power plant will inject its full capacity. However, recently, a new understanding was applied to non-controllable renewable hybrid power plants sharing the same connection. As it combines two or more (generally) complementary sources, the probability of the two or more sources achieving the maximum simultaneously would be very small.

Therefore, the benefit of complementarity between sources composing hybrid power plants could also be captured at the network level. In this case, the current regulatory framework allowed a reduced amount of NAC lower than the sum of the individual sources' installed capacity within hybrid power plants. This feature was considered in the proposed regulation, [25], regarding the flexibilization of NACs, wherein hybrids can contract M between the highest source installed capacity and the total installed capacity of the hybrid plant. This regulatory innovation allows for relevant NAC cost savings while incentivizing the hybridization of complementary sources that relieve network expansion needs. Yet, annually, the hybrid generation is allowed by regulation to reduce or increase the NAC. We shall remark that in October of 2022, it was published the first flexibilization for a solar-wind hybrid power plant to establish M in a range between 471 MW and 590 MW.

Nevertheless, a penalty must be paid when generation injection surpasses the network-access contract M. According to [33], generators are subject to a monthly penalty when the injection is higher than the contracted amount M. In practical cases, the heavy penalties incurred are set to discourage the injection of any additional power beyond the NAC, which is, thereby, curtailed in real-time operation. In this context, the decision to lower the NAC below the total installed capacity implies a decision to lower the maximum generation. Thus, the evaluation based on this assumption can be seen as a conservative one as other economically relevant alternatives could be combined (e.g., with batteries to shift the generation, production of green hydrogen, and agricultural usages, among others); albeit their evaluation lies out of the scope of this paper.

4.2. Firm Energy Certificates in Brazil

The concept of FEC is an energetic reliability stamp, measured in average MW (avgMW), which aims to quantify the amount of energy a generator can reliably supply. Therefore, the FEC is used as a relevant generation expansion index in planning studies and in new capacity auctions [34]. For instance, the system planner (EPE – *Empresa de Pesquisa Energética*) defines the demand to be contracted in long-term contracts (10 to 30 years) according to the projected demand excess in relation to the total amount of FECs. This general concept is currently implemented in Brazil as an allocation among generators of shares of a global long-term energetic supply capacity index, which is calculated based on dispatch simulations by the system planner and issued by the Ministry of Mines and Energy. This happens because the total energy that a coordinated system can supply with many hydros operating under different inflow regimes and interconnected by complex cascades is higher than the sum of the energies that would be achieved if operated individually. Therefore, the FEC of dispatchable units (units operating under the coordination of the national system operator) is calculated by EPE as a share of the system-global energetic supply capacity. We refer to [11] and [34] for further discussions and references.

Nevertheless, for non-controllable renewables (considered non-dispatchable units), such as wind and solar sources, the FEC is issued based on the expected value or quantiles of the annual average historical generation availability, depending on the source. Certification companies calculate historical variances and other parameters according to each technology. For instance, for wind power plants, the 10^{th} percentile of the annual generation (in average MW) is used, whereas for solar units, the 50^{th} percentile is adopted. Similarly, the average production considering historical inflows is used for run-of-river small hydro plants. In addition to the previous differences between sources, the assessment and revision procedures are mainly based on the historical average. Therefore, although the regulation aims at assigning and revising FECs of non-controllable renewables that are intrinsically associated with their expected annual generation capacity, for historical reasons, the current regulation uses a different methodology to establish the FEC for each type of source. Furthermore, besides its relevance to planning studies, the FEC also has a significant impact on market decisions, as it defines the maximum regulatory amount that a generator can sell in forward contracts (see [34] for further details). Thus, the discrepancies among the FEC calculations constitute a regulatory distortion that can discriminate sources in both long-term studies, auctions, and forward market competitiveness. It is interesting to mention that none of the methodologies acknowledges the strong generation seasonality to which most of these sources are subject, and only wind generators have their FEC calculated based on a reliability index (low percentile).

In addition to the above regulatory incompatibilities, the recent interest in hybrid power plants has triggered further issues. First, how to calculate a single FEC for a hybrid power plant composed of two different sources, e.g., wind and solar, each of which with its own FEC calculation methodology? Second, how to consider in the FEC of hybrid units the generation curtailments imposed by the economic response of reducing the NAC? This introduces a second layer of complexity, as the FEC calculation should be agnostic to the source in renewable auctions and planning studies. While reducing the NAC, generation companies and the system planner benefit from reduced NAC payments and reinforcement needs, respectively, on the other hand, the energetic supply contributions to the system and the forward contracting limits must be compatibilized by coherently reduced FECs. *Hence, the coherence between the main transmission and generation expansion indexes (NAC and FEC) for non-controllable renewables and hybrid power plants relies on a unified and non-discriminatory FEC calculation methodology.* As depending on the investor's risk attitude, the FEC may limit the optimal forward involvement, the proposed FEC calculation for hybrid units will be addressed first.

5. The proposed unified FEC for renewables and hybrid power plants

Based on the coherence requirement described at the end of the previous Section, we propose a unified FEC for non-controllable sources that can coherently accommodate 1) the hybridization of different sources, 2) capture the complementarity synergy among them, and 3) consider the effect of

NAC. For didactic purposes, hereinafter, we will consider only the case of two sources, wind and solar. Notwithstanding, the whole developments and proofs in the sequel can be easily extended to the case of more than two generic non-controllable sources.

Additionally, bearing in mind the parsimony principle, in this Section, we will present the simplest version of our proposal, the *truncated expected-value-based FEC* (TEV-FEC), which constitutes the minimal change in the current regulation needed to make a coherent unified and non-discriminatory framework for renewables. Additionally, it is important to highlight that if the aim of FECs in the current Brazilian regulation relies on annual energetic contributions, expectations (or averages) play a better role in quantifying the integral of the energy supplied within a given period than quantiles. Nonetheless, we discuss possible extensions in the Appendix.

5.1. The unified truncated expected-value-based FEC for renewables and hybrid power plants

Considering a vector $\mathbf{G}$ with historical generation availability for any given non-controllable renewable-based generator, i.e., $\mathbf{G} = [G_1, ..., G_{|\mathcal{H}|}]'$, and a network-access contract amount M, the FEC of the power plant can be defined as follows:

$$\mathbb{F}(\mathbf{G}, M) = \frac{1}{|\mathcal{H}|} \sum_{t \in \mathcal{H}} \min\{G_t, M\}. \tag{1}$$

The function in expression (1) defines the truncated expected-value-based FEC (TEV-FEC), which is source agnostic and can be used for any non-controllable renewable. It is the average (weighted sum) of the minimum between the renewable generation and the NAC amount. As it is the average of maximums between linear functions, the TEV-FEC is concave on both $\mathbf{G}$ and M. For didactic purposes, hereinafter, we consider a (normalized) hybrid power plant of 1 MW total installed capacity composed of a x-MW solar generator and a $(1-x)$-MW wind generator. Within this context, based on expression (1), we can define the FEC of any hybrid power plant as $\mathbb{F}(\mathbf{G}^H(x), M)$, where $\mathbf{G}^H(x)$ is defined as follows:

$$\mathbf{G}^H(x) = x\mathbf{G}^S + (1-x)\mathbf{G}^W. \tag{2}$$

Thus, the TEV-FEC of non-hybrid units rests on the specific cases of $x = 0$ and $x = 1$. Note that in (2), we need to consider paired historical generation for the wind and solar sources, i.e., $G_t^H(x) = xG_t^S + (1-x)G_t^W$ for $t \in \mathcal{H}$, and that both wind and solar generation vectors consider normalized generation availability in percentages of their maximum installed capacity to meet the one-MW definition above. It is worth mentioning that because $\mathbf{G}^H(x)$ is linear on x, $\mathbb{F}(\mathbf{G}^H(x), M)$ is concave on x. So, based on (1) and (2), we can state the following theorem:

Theorem 1: *The TEV-FEC of the hybrid power plant composed of* $x100\%$ *of solar and* $(1-x)100\%$ *of wind and with a NAC amount* M *is super-additive, i.e., is greater or equal to the sum of the FEC of its parts splitting* M *in proportion to* x *and* $1-x$*, for any* $x \in [0,1]$*. In mathematical terms, it means that*

$$\mathbb{F}\big(\mathbf{G}^H(x), M\big) \geq \mathbb{F}\big(x\mathbf{G}^S, xM\big) + \mathbb{F}\big((1-x)\mathbf{G}^W, (1-x)M\big). \tag{3}$$

Proof: As we know that the minimum between two linear functions is a concave function and positive homogeneous [35], the following inequality holds $\forall t \in \mathcal{H}$ and $x \in [0,1]$:

$$\begin{aligned}\min\{xG_t^S + (1-x)G_t^W, xM + (1-x)M\} &\geq x\min\{G_t^S, M\} + (1-x)\min\{G_t^W, M\}\\ &= \min\{xG_t^S, xM\} + \min\{(1-x)G_t^W, (1-x)M\}.\end{aligned} \tag{4}$$

By averaging the first and the last term of (4) we have:

$$\begin{aligned}\frac{1}{|\mathcal{H}|}\sum_{t\in\mathcal{H}}\min\{xG_t^S + (1-x)G_t^W, xM + (1-x)M\} \geq \frac{1}{|\mathcal{H}|}\sum_{t\in\mathcal{H}}\min\{xG_t^S, xM\} +\\ \frac{1}{|\mathcal{H}|}\sum_{t\in\mathcal{H}}\min\{(1-x)G_t^W, (1-x)M\}.\end{aligned} \tag{5}$$

It happens that the left-hand-side of (5) meets the definition of the FEC for a hybrid power plant, whereas the right-hand-side meets the sum of the FECs of its parts when M is split in proportion to x and $1-x$, i.e.,

$$\mathbb{F}\big(\mathbf{G}^H(x), M\big) \geq \mathbb{F}\big(x\mathbf{G}^S, xM\big) + \mathbb{F}\big((1-x)\mathbf{G}^W, (1-x)M\big). \ \blacksquare \tag{6}$$

Remark 1: *Theorem 1 tells us that there is a potential gain of synergy in terms of FEC associated with hybrid units, which constitutes a relevant additional incentive for hybridization in planning studies and new capacity auction as for the same transmission cost, the hybrid power plant may deliver a higher energetic contribution to the system, translated by the FEC gain. We will further see in our empirical studies that this gain, for a hybrid power plant with* $x \in (0,1)$*, is maximum on values of NAC lower than the sum of the total installed capacities, i.e.,* $M < 1$*. This provides evidence that the proposed TEV-FEC connects the incentives for hybridization with the benefit of transmission expansion cost savings, a timely contribution to the current Brazilian regulatory system.*

Remark 2: *If the FEC is based on the expected value of the annual average generation, the FEC annual revision process should not consider* ad hoc *intervals for triggering an FEC value revision. Instead, the critical intervals of a hypothesis test for the mean should be used. Although the definition* *of such a process is out of the scope of this paper, typical error type I and II analysis can be used to define intervals tailored to each power plant, thereby acknowledging their individual and intrinsic variance.*

Corollary 1: ***Theorem 1*** *is directly extensible for the more general case where the hybrid unit is composed of N non-controllable renewable sources, each of which with a generation profile* $\boldsymbol{G}^{(i)}$ *for* $i = 1, ..., N$. *Formally, if we consider N renewable sources and replace expression* (2) *with* $\boldsymbol{G}^H(x) = \sum_{i=1}^{N} x_i \boldsymbol{G}^{(i)}$, *for any vector of participation shares* $\mathbf{x} = \{x_1, ..., x_N\}$, *such that it recovers the total hybrid power plant power, i.e.,* $\sum_{i=1}^{N} x_i = 1$, *with* $x_i \geq 0$, *for* $i = 1, ..., N$, *expression* (3) *in* ***Theorem 1*** *could be restated as* $\mathbb{F}\big(\boldsymbol{G}^H(x), M\big) \geq \sum_{i=1}^{N} \mathbb{F}\big(x_i \boldsymbol{G}^{(i)}, x_i M\big)$.

Proof: As the main part of **Theorem 1**'s proof relies on Jensen's inequality embedded into the definition of a concave function, the proof follows from generalizing the steps of **Theorem 1**'s proof. In this sense, by the same principles (concavity and positive homogeneity [35]), the inequality (4) could be rewritten as $\min\{\sum_{i=1}^{N} x_i G_t^{(i)}, \sum_{i=1}^{N} x_i M\} \geq \sum_{i=1}^{N} \min\{x_i G_t^{(i)}, x_i M\}$. Thus, by averaging in time the left- and right-hand-side of this inequality, precisely as done in (5), we reach the N-source generalized statement of **Theorem 1**. ■

5.2. Illustrative empirical analysis of the proposed TEV-FEC

The key aspect behind the inequality (and possible gain) in **Theorem 1** is the fact that the combination of two complementary sources may reduce the risk of curtailments, which happen whenever $xG_t^S + (1-x)G_t^W > M$. It is easy to see this fact, as the cap (truncation) on M is the only part that, if removed, would turn (3) into equality, which is due to the linearity property of the expected value operator. To empirically quantify this gain, we can define it as the difference between the TEV-FEC for the hybrid power plant and the sum of the TEV-FEC for the individual sources composing it, i.e.,

$$gain(x, M) = \mathbb{F}(\mathbf{G}^H(x), M) - [\mathbb{F}(x\mathbf{G}_t^S, xM) + \mathbb{F}((1-x)\mathbf{G}_t^W, (1-x)M)] \tag{7}$$

Let's consider the hybrid power plant, which is composed of solar and wind sources, with a total installed capacity of 1 MW. To illustrate the gain for different values of M, we arbitrarily select $x = 0.5$ (hybrid half wind/solar) and plot the $gain(0.5, M)$ in Figure 2. The summation of wind (green line) and solar (yellow line) is represented by the segmented black line, while the hybrid is the continuous black line. The gap between these two black lines represents the gain of a hybrid power plant in terms of FEC, which is highlighted in the bar graph below. It must be noted that the *gain* is zero at the borders of M, especially important where the network-access contract amount reaches the total installed capacity. Below that, particularly in the range $M \in [0.3, 0.6]$ we see a considerable gain of hybrid plants in terms of FEC.

Additionally, applying the same calculus in Figure 3, for x ranging from 0.0 to 1.0, it is possible to see the highest gain of hybrid behavior according to different share of sources. We observe that the maximum *gain* happens for a particular M, which depends on each x. In Figure 3, we can observe that the maximum FEC gain is achieved with $x = 0.5$. However, these peaks should not define the optimal

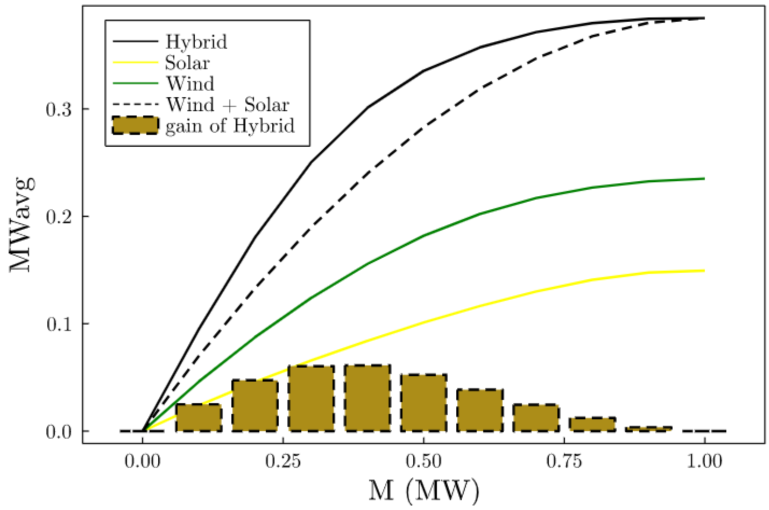

Figure 2: FEC Comparison of Hybrid and spitted sources for $x = 0.5$.

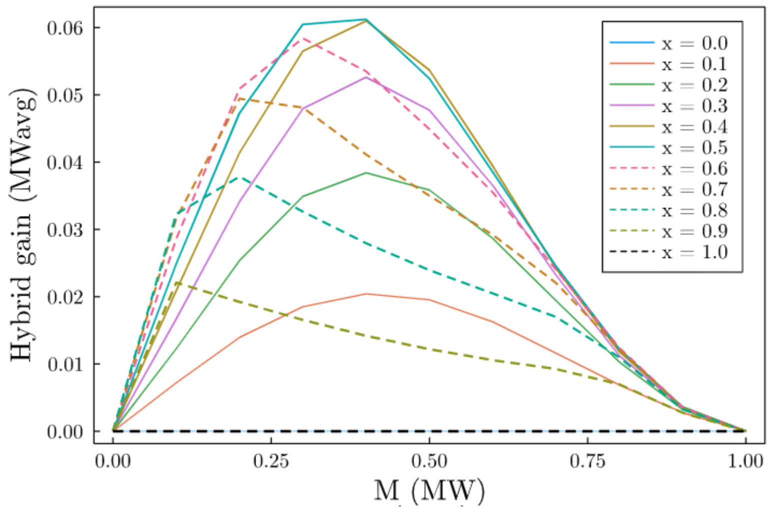

Figure 3: FEC gain compared to separated sources, according to x.

strategy for M and x. The relationship between higher revenue and higher M is not straightforward and mainly relies on the risk-adjusted economic strategy of each investor. In this context, their optimal value should be jointly defined considering the non-trivial relations between curtailments reducing spot revenues, NAC payments, and the price-and-quantity risk due to the forward involvement. Therefore, in the next Section, the interaction between M, x, and forward involvement Q for a hybrid power plant is characterized through a risk-adjusted optimal joint contracting and share strategy defined by a two-stage stochastic optimization model.

6. Co-optimization of network-access and forward contracts

6.1. Generators revenue, costs, and risk profile

The generator's net revenue can be expressed as the difference between the revenue (8) and costs (9). So, the net revenue is a function of the network-access contract M, forward contract Q, and share of solar x. The annual revenue $\tilde{R}$, which is a random variable, comprises the contract income plus the revenue in the spot market regarding the differences between the generation and the contract as follows:

$$\tilde{R}(Q, M, x) = \sum_{t \in \mathcal{T}} [pQ + (\hat{\tilde{g}}_t^H(M, x) - Q)\tilde{\pi}_t]. \tag{8}$$

The cost is a deterministic function of the NAC amount and the proportion of renewable energy sources multiplied by their CAPEX, C^S and C^W.[3] It is represented as follows:

$$C(M, x) = \sum_{m \in \mathcal{M}} Mc_m + xC^S + (1 - x)C^W. \tag{9}$$

Given the previous equations, it is clear that the optimal point regarding network-access amount M is not necessarily the one with the maximum energy. In fact, as the cost of NAC increases linearly with M, and the effective generation output of the hybrid power plant $\hat{\tilde{g}}_t^H(M, x)$ is a random non-decreasing concave function of M, there should be a value of M for which the incremental marginal cost with NAC tariff of increasing the NAC amount is equal to the incremental marginal certainty equivalent (utility) with additional spot revenues.

To assess the value of random variables, in this paper, we make use of a coherent risk measure, namely, the conditional value at risk, to generate a certainty equivalent as per [36]. To do that, let us consider a risk profile characterized by a certainty equivalent (ρ) based on the Conditional Value at Risk (CVaR). So, in this setting, given a random revenue $\tilde{R}$, the certainty equivalent (in \$) is defined as follows:

$$\rho_{\alpha,\lambda}(\tilde{R}) = \lambda CVaR_{\alpha}(\tilde{R}) + (1 - \lambda)E(\tilde{R}). \tag{10}$$

This certainty equivalent metric can be recast as a linear optimization problem by means of a linear programming representation for the CVaR in $\rho_{\alpha,\lambda}$ according to expressions (7) and (8) in [37], firstly proposed in [37]. For a discrete distribution of $\tilde{R}$, with scenarios and probabilities given by

[3] Our initial economic analysis aims to study the tradeoffs associated with integrating two sources with different generation profiles and installation costs. Therefore, for simplicity purposes, this work omits detailed consideration of corporate finance cashflow structures such as taxes, local tariffs, debt principal and interest payments, etc.

$\{(R_\omega, 1/|\Omega|)\}_{\omega\in\Omega}$, $\rho_{\alpha,\lambda}$ can be represented as follows:

$$\rho_{\alpha,\lambda}(\tilde{R}) = \lambda \max_{z} \Big\{ z - \sum_{\omega\in\Omega} \frac{(z - R_\omega)|^+}{(1-\alpha)|\Omega|} \Big\} + (1-\lambda)\frac{1}{|\Omega|}\sum_{\omega\in\Omega} R_\omega. \tag{11}$$

The above formulation is suitable for linear programming problems as widely used in the related literature (e.g., see [12] and [13]).

6.2. Co-optimization model

In this Section, we present the proposed risk-adjusted two-stage stochastic model to define 1) the optimal joint contracting strategy for both the forward market and the network-access contracts (Q^*, M^*), and 2) the optimal share (x^*) of sources for a one-MW hybrid power plant. The mathematical formulation of the model is as follows:

$$\max_{M,Q,x,\hat{g}^H_{t,\omega},\hat{G}^H_t} \quad \rho_{\alpha,\lambda}\Big(\sum_{t\in\mathcal{T}}[pQ + (\hat{g}^H_t - Q)\tilde{\pi}_t]\Big) - \sum_{m\in\mathcal{M}} Mc_m - xC^S - (1-x)C^W \tag{12}$$

s.t.:

$$\hat{g}^H_{t,\omega} \le M \qquad \forall\, t\in\mathcal{T}, \omega\in\Omega \tag{13}$$

$$\hat{g}^H_{t,\omega} \le (1-x)g^W_{t,\omega} + xg^S_{t,\omega} \qquad \forall\, t\in\mathcal{T}, \omega\in\Omega \tag{14}$$

$$\hat{G}^H_t \le M \qquad \forall\, t\in\mathcal{H} \tag{15}$$

$$\hat{G}^H_t \le (1-x)G^W_t + xG^S_t \qquad \forall\, t\in\mathcal{H} \tag{16}$$

$$Q \le \frac{1}{|\mathcal{H}|}\sum_{t\in\mathcal{H}} \hat{G}^H_t \tag{17}$$

$$M, Q, \hat{g}^H_{t,\omega}, \hat{G}^H_t \ge 0, \text{and } x\in[0,1] \tag{18}$$

In (12)–(18), the objective function comprises the maximization of the CVaR-based certainty equivalent, (10), applied to the net revenue, i.e., the difference between expression (8) and (9). As costs are deterministic, and the $\rho_{\alpha,\lambda}$ is shift additive (see [36]), the cost can be considered out of the certainty equivalent. Additionally, by considering $\hat{g}^H_{t,\omega}$ as a decision variable, expressions (13) and (14), impose that this variable lies in the hypograph of the hybrid power plant truncated generation, i.e., that $\hat{g}^H_{t,\omega} \le \min\{(1-x)g^W_{t,\omega} + xg^S_{t,\omega}, M\}$. Actually, as 1) $\hat{g}^H_{t,\omega}$ is multiplied by positive coefficients (as spot prices are positive, i.e., $\tilde{\pi}_t \ge 0$) and 2) $\rho_{\alpha,\lambda}$, for $\lambda > 0$, is a non-decreasing function (see [36]), the optimal solution will always be attained on the equality, i.e., $\hat{g}^{H*}_{t,\omega} = \min\{(1-x)g^W_{t,\omega} + xg^S_{t,\omega}, M\}$. The same rationale applies to $\hat{G}^H_t$ and expressions (15) and (16), which are used to reproduce the truction on M of the historical generation availability profile used to define the final hybrid-power plant FEC. Finally, expression (17) defines the regulatory limit for the forward involvement based on the FEC, and (18) defines the limits of each variable. It is important to mention that by adjusting expressions (15)–(17), the model can be modified to consider other regulatory designs for the FEC. Model (12)–(18) can be recast as a linear optimization problem by replacing $\rho_{\alpha,\lambda}$ in (12), with its linear counterpart (11). For the sake of brevity and to avoid redundancy, we omit this reformulation.

It is important to notice that in the model (12)–(18), two data sets are used for different yet interrelated purposes. First, the FEC is endogenously determined according to the value of the NAC and renewable share decision variables, but using historical generation data $\{(G_t^W, G_t^S)\}_{t\in\mathcal{H}}$. In contrast, the forward involvement, the NAC amount, and the renewable share are decision variables selected in the optimization problem based on their contribution to the objective function, which is calculated using simulated data for the future horizon, namely, $\{(g_{t,\omega}^W, g_{t,\omega}^S)\}_{t\in\mathcal{T},\omega\in\Omega}$, and considering their interaction with the FEC. In this context, any discrepancy between historical data and future generation scenarios foreseen by the decision maker can be accounted for in the decision model based on the selection of these two data sets. Additionally, it is worth mentioning that the proposed model is not restricted to regulatory systems where the FEC exists. For instance, in any other system where the FEC is not relevant for the decision-making process, one can drop FEC constraints (15)–(18), and use the model to define Q, M, and x, or a subset of it, depending on the application.

Finally, it is important to highlight that model (12)–(18) can be generalized to the general case of N sources. To do that, one needs to replace the last two terms of the objective function regarding the CAPEX of wind and solar with the more general expression $sum_{i=1}^{N} x_i C^{(i)}$, with $C^{(i)}$ representing the CAPEX of each source. Additionally, the right-hand-side of the simulated and historical hybrid generation in (14) and (16) should be replaced with the general sum among all the N sources. Finally, the variable x should be replaced with the more general vector of shares $\mathbf{x} = \{x_1, ..., x_N\}$, and constraints imposing $\sum_{i=1}^{N} x_i = 1$ and $x_i \geq 0$ for all $i = 1, ..., N$ should be included in the model to ensure that the sum of the generation, installed capacity, and CAPEX from the N sources is equal to the generation, power capacity, and total CAPEX of the hybrid unit.

7. Case Studies

In this section, we present two case studies. First, we test the co-optimization of forward and network-access contracts idea for a hybrid power plant composed of 50-50 % (arbitrarily selected) wind and solar. So, in this case study, model (12)–(18) is used disregarding the CAPEX parcel in the objective function and with an additional constraint imposing $x = 0.5$. In the second study, we let x be co-optimized with M and Q. We study the optimal solution as a function of the annualized CAPEX of two sources composing the hybrid power plant, thereby considering the complete objective function (12). We also conduct sensitivity analyses on the shares (x) to study the effect of the share in the optimal contracting strategies, i.e., on the optimal responses $M^*(x)$ and $Q^*(x)$. Finally, the alignment between the generator's economic-driven decisions and the system benefits is analyzed. In all case studies, we considered a risk-averse attitude defined by $\lambda = \alpha = 0.95$, 200 simulated scenarios characterizing the future generation profiles and spot prices $\{(g^W_{t,\omega}, g^S_{t,\omega}, \pi_{t,\omega})\}_{t\in\mathcal{T},\omega\in\Omega}$, and an hourly horizon for the target year of 2025. So, we used $|\Omega| = 200$ and $|\mathcal{T}| = 8760$. Finally, the set of historical data $\{(G^W_t, G^S_t)\}_{t\in\mathcal{H}}$ considered all hours from the beginning of 1980 to the end of 2017.

The model is implemented in Julia Language (JuMP) and solved by Gurobi. The data set used in this paper is available at [29]. We used a NoteBook Intel(R) Core(TM) i7-8565U with 4 cores (1.99 GHz each) and 8 GB of RAM.

7.1. Case Study 1: Co-optimizing network-access and forward constracts

In this first case study, we assume a hybrid power plant half solar, half wind, i.e., $x = 0.5$. First, we assume a neutral forward market with a forward price p equal to the expected value of the average annual spot price, i.e., 83 R\$/MWh, a constant network-access tariff $c_m = 7$ R\$/kW/month and null CAPEX, $C^W = C^S = 0$. The effect of different forward prices will be further studied. However, first, we showcase the relevance of optimizing both forward and network-access contracts. To do that, we benchmark the results of our model with the base case, where the network-access contract remains equal to the total installed capacity. Thus, the benchmark model also comprises another constraint, i.e., $M = 1.0$.

For the benchmark, we find $Q^* = 0.3294$ and an objective value equal to $150,796$\$ (Expected Value of $188,875$\$ and CVaR of $148,791$\$). Then, by co-optimizing both variables (M and Q), we find $M^* = 0.5548$ (44.52% lower than the benchmark), $Q = 0.3177$ (3.57% lower than the optimal forward contracting level in the benchmark) and an objective value of $178,159$\$ (18.15% higher than that obtained in the benchmark) (Expected Value of $210,132$\$ and CVaR of $176,476$\$). In other words, the co-optimization significantly reduces the network-access contracting amount to a value that is only 10.96% higher than the installed capacity of each source (recall that in this case study, each source has 0.5 of the total installed capacity). On the forward contracting side, it is worth mentioning that the new joint contracting strategy, which is responsible for reducing 44.52% of the network-access annual costs, is made without significantly altering the forward involvement strategy (only 3.57% of reduction in comparison to the benchmark). Hence, the significant improvement in the risk-adjusted revenue metric is mostly due to the reduction of network-access expenditures. Notwithstanding, the 3.57% adjustment in the forward market is necessary to compensate for the price and quantity risk due to the reduction in the generation profile. Regarding the generation curtailment, it is worth mentioning that, in contrast to the significant reduction in the NAC amount and related fixed cost savings (44.52%), the expected self curtailment, implemented to avoid exceeding the reduced NAC amount M^*, is only 7.63% of the total expected value of the available generation of the hybrid power plant. In terms of expected revenue in the spot market, this curtailed energy represents only 6.28% of the total expected revenue of the co-optimized case.

To further analyze the co-optimized strategy, we can vary the forward contract price to simulate different market conditions. To do that, we run the model (12)–(18) with $p = p_0\beta$, where $p_0 = 83$ R$/MWh (neutral market) and $\beta \in \{0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0\}$. In Figure 4, we can see that the network-access contract M^* and the forward contract Q^* increase, especially the first, as the contract price grows, which is somewhat expected. However, it is interesting to see that the NAC grows faster than forward involvement, whereas M^* does not surpass 0.8102 and Q^* does not surpass 0.3805. This optimal economic behavior, which considers a balance between the generation investor's commercial strategy (in both forward and spot markets) and transmission utilization, brings relevant evidence that hybrid power plants should be allowed to reduce their NAC amount. Additionally, the benefits are intrinsically linked to an individual decision to shave generation peaks, which change the generation profile and thereby the energetic contribution to the system. Hence, this is further evidence in favor of revising the regulatory framework to ensure it acknowledges this link on both the FEC and NAC payments in a coherent and non-discriminatory manner.

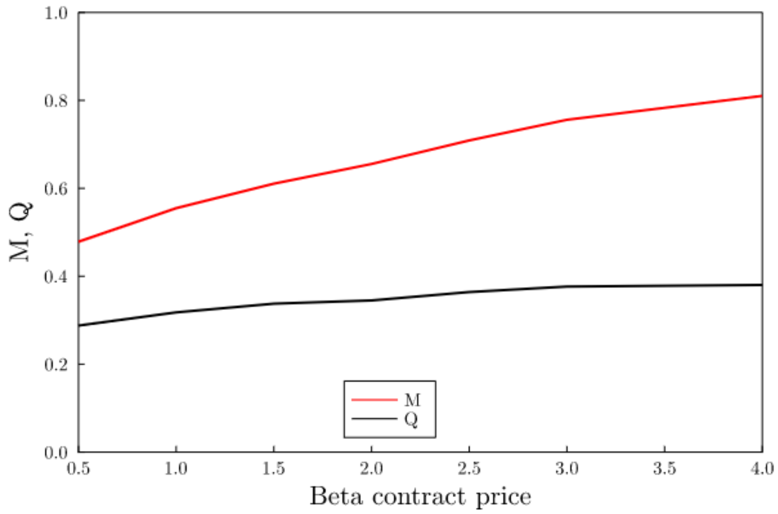

Figure 4: Network-access contract and Forward Contract Q according to β contract price.

7.2. Case Study 2: Sensitivity on the CAPEX of solar and wind and the optimal share of sources

To perform a more comprehensive analysis of the optimal share (x), we must account for the annual CAPEX of the different sources composing the hybrid power plant. To study the optimal joint contracting strategy and the optimal share of the hybrid power plant, in this subsection, we run model (12)–(18) with all its term and no additional constraints to define the optimal vector $[M^*, Q^*, x^*]$. According to our studies, we find that for $C^S = C^W$, the best solution is $x^* = 0$. So, in this case study, we run our model for different combinations of $C^S < C^W$. To facilitate this sensitivity, we parameterize $C^S = \gamma \cdot C^W$. As per [38], in Brazil, the CAPEX for wind power plants ranges from 3,200 to 5,500 R$/installed-kW, whereas the CAPEX for solar units ranges from 2,500 to 5,000 R$/installed-kW. So, for $C^W = \kappa{\cdot}4,000$ R$/installed-kW (within the range for wind power), we run a sensitivity analysis on $\gamma = \frac{C^S}{C^W} \in [0, 1]$. To rescale standardized CAPEX costs for annualized ones compatible with the revenue horizon and convert it from \$/kW to \$/MW, a constant $\kappa = 1/25 \cdot 1,000$ is used.

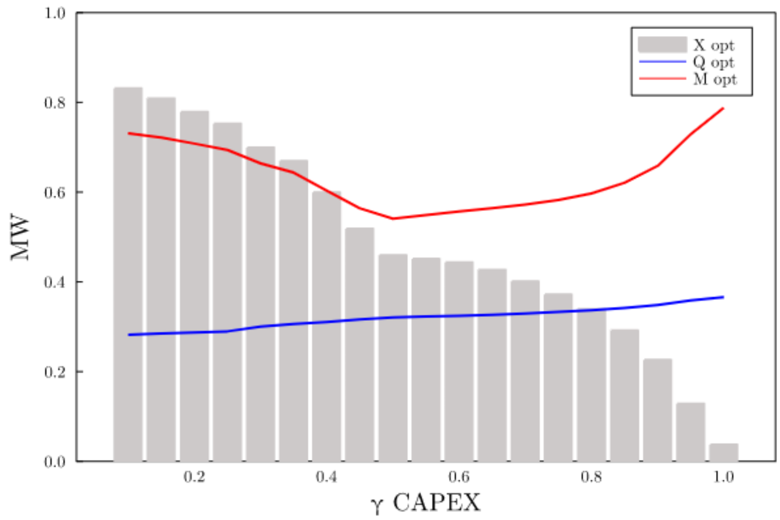

Figure 5: Optimum x solar, M and Q according to CAPEX defined by γ.

Figure 5 depicts the co-optimized strategy $[M^*, Q^*, x^*]$ for each value of γ. It is clear that for reasonable values of γ, e.g., $\gamma = 0.8$ ($C^W = \kappa{\cdot}4,000$ and $C^S = \kappa{\cdot}3,200$), hybridization becomes the best option. It is worth noting that the CAPEX configuration resulting in the most efficient utilization of the network resources (from the system point of view, i.e., with minimum NAC) is obtained with $\gamma = 0.5$ ($C^W = \kappa{\cdot}4,000$ and $C^S = \kappa{\cdot}2,000$). Although this point is, so far, out of the range of CAPEX for solar units, it would produce an optimal co-optimized strategy with $[M^* = 0.5410, Q^* = 0.3210, x^* = 0.4589]$.

Notwithstanding, for $\gamma = 0.8$ (within the range of CAPEX for solar units), the best strategy is $[M^* = 0.5968, Q^* = 0.3367, x^* = 0.3388]$, where the transmission utilization is significantly reduced to approximately 60% of the utilization imposed by the previous regulation, only 10.3% higher than the most efficient utilization obtained with $\gamma = 0.5$. Additionally, we can see that $M^* < 0.8$ for all values of γ. To further illustrate this trend, Figure 6 showcases the optimal certainty equivalent (and its parcels, namely, the expected value and CVaR), the joint NAC and forward contracting strategies, and the proposed TEV-FEC for each value of x.[4] Note that the incentive for reducing the NAC amount is prevalent even for suboptimal values of x (see the red line in Figure 6), where no value of $M^*(x)$ is higher than 0.81. These results showcase the robust economic incentives to reduce transmission needs.

Another relevant insight from Figure 6 is related to the long-term generation-profile average, represented by the FEC (green line). It is worth noticing that the FEC monotonically decreases from a 100% wind-based power plant configuration ($x = 0$) towards a 100% solar configuration ($x = 1$). This happens because the average generation of the selected wind power plant is higher than the

[4]This sensibility is obtained by running the complete model (12)–(18) with an additional constraint imposing x to be equal to each value considered in the figure.

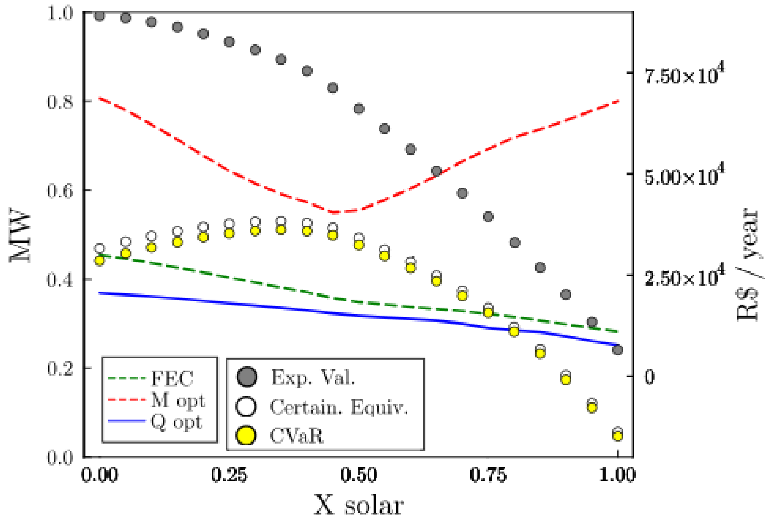

Figure 6: Objetive and CVaR values, Q, FEC and M according to x solar, for $\gamma = 0.8$.

selected solar, which is typical of the northeastern region of Brazil. This also helps us to understand the monotonically decreasing expected value (risk-neutral metric). Notwithstanding, the typical wind power plant generation profile, although presenting a higher annual average (FEC), also comes with higher uncertainty. This explains the relevant gap between the expected value and the CVaR metrics and the difference between the optimal contracting strategy $Q^*(x)$ and the FEC for $x = 0$. In this context, the typical hedging action is to reduce the forward involvement relatively to the average generation profile (FEC) to mitigate the price and quantity risk. However, this hedging structure cannot be achieved by typical risk-neutral analyses based on average profiles and is only possible to be captured by means of a risk-adjusted strategy, as proposed in Section VI.A. So, the optimal share $x^* = 0.3388$ found for $\gamma = 0.8$ considers not only the balance between deterministic NAC payments and forward market revenues but also a compromise with the price and quantity risk through an integrated risk-adjusted co-optimized strategy for M, Q, and x. Finally, it is relevant to note that the break of the rapid decrease pattern in the TEV-FEC after the minimum value of M shows that the proposed FEC calculation is capable of capturing the interaction with M and x, providing the system planner with a coherent measure of generation contribution according to each hybrid power plant configuration.

8. Conclusion

This paper proposed a unified formulation for the firm energy certificates of renewables and hybrid power plants in Brazil. Based on that, a co-optimization tool for jointly defining the optimal network-access and forward contracting strategy was proposed and tested with realistic data from typical profiles of wind and solar generation. The proposed truncated expected-value-based firm energy certificate (TEV-FEC) constitutes the minimal change in the current regulation in Brazil needed to make a coherent, unified, and non-discriminatory framework for renewables and hybrid power plants. We demonstrate relevant insights based on realistic data from the northeastern region of the Brazilian power system, where the largest amount of wind and solar power plants are installed.

Within the limitations of the presented case study, which include all assumptions of the proposed model and the specific data, the results and analyses carried out in this work allow us to convey the following concluding remarks:

- The risk-averse co-optimization of the hybrid power plant shares with the NAC and forward contracting strategies can yield significant economic gains.
- The reduction in the NAC with respect to the benchmark value (total installed capacity) is responsible for most of the monetary benefit, whereas the curtailed energy surplus is relatively low, thereby justifying the reduction in NAC and fixed expenditures.
- Based on typical values of CAPEX ($4,000$ R$/installed-kW for the wind and $3,200$ R$/installed-kW for the solar) and generation profiles of wind and solar power in the Northeastern region of Brazil, hybridization is the best economical option for the generation investor.
- In the aforementioned CAPEX configuration, the best joint strategy for the NAC, forward involvement, and source composition is, respectively, $M^* = 0.5968, Q^* = 0.3367, x^* = 0.3388$. It is important to highlight that, in this case, the transmission utilization is reduced to approximately 60% of the utilization imposed by the previous regulation.
- Results also indicate a consistent and robust alignment between the generator's best strategy and reducing the system's transmission resource utilization. We show that in all analyzed cases, including different values of CAPEX and source compositions, the best strategy is to reduce the NAC.
- Alternatively, although not explicitly calculated in this paper, results suggest that the inclusion of solar panels to complement existing wind power projects in a hybrid generation scheme (following the proportion given by the proposed model) may not require the purchase of the additional installed capacity in NACs.
- Finally, results demonstrate that the proposed TEV-FEC is capable of capturing the benefits of renewable generation complementarity and the effect of reducing the transmission access amount in a coherent and non-discriminatory manner among non-controllable renewables.

We highlight as relevant future research avenues the following topics: 1) the study of the regulatory incentives and the optimal trading strategy for hybrid units considering more sophisticated FECs, e.g., the FEC extension proposed in the appendix; 2) the extension of [14] to include NAC co-optimization and its incentives in the revenue-adequacy analysis for different partitioning schemes (e.g., Shapley, Aumann-Shapley, Nucleolus) applied to a pool of renewables within a given bus or "transmission-free" zone; 3) the expansion for the results in this paper for $n > 2$ units; 4) the expansion of the model to include storage; 5) the use of cooperative game theory such as that proposed in [14] to share the total FEC of a pool of renewables composing a hybrid unit; 6) the study of the annual revision processes for the proposed TEV-FEC based on hypothesis tests.

9. Acknowledgements

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Appendix

In this Appendix, we discuss the extension of the proposed TEV-FEC for a hybrid power plant to consider seasonality, i.e., we consider $\mathbb{F}_m(\mathbf{G}^H(x), M)$, where m represents subperiods of the year. To do that, we just need to consider interannual, such as monthly or quarterly, calculations of (1). For didactic purposes, hereinafter, we use a monthly discretization. Thus, for each month $m \in \{1, ..., 12\}$, one just needs to filter from the complete historical data $\mathcal{H}$ used to calculate (2), the generation associated with hours in month m, i.e., $\mathcal{H}_m$, as follows:

$$\mathbb{F}_m(\mathbf{G}^H(x), M) = \frac{1}{|\mathcal{H}_m|} \sum_{t \in \mathcal{H}_m} \min\{G_t^H(x), M\}. \tag{19}$$

It is easy to see that **Theorem 1** is valid for (19), as it replicates the same functional structure to subsets of the data.

Nevertheless, a simpler and bid-based version for the FEC of non-controlled renewables could also consider declared values with annual verification and penalties. The proposed TEV-FEC could be used for the first year to ensure a data-driven initial value and serve as a reference for market monitoring purposes. In this context, the agents would internalize all their market and hybridization strategies within their declared value for the FEC, and an annual penalization scheme would induce the agents to select their declared value carefully. This freedom to define the FEC is compatible and conceptually related to the newly passed regulatory guideline for the NAC of hybrid power plants. To this end, assuming that the maximum amount injected is already controlled by the NAC, the declared FEC could be obtained by the proposed co-optimization model. In this case, the model would also consider an additional variable for the FEC, namely F. Thus, the stochastic penalty related to not achieving the annual average for the next year (or any other monthly target, e.g., in the case of a seasonal FEC) could be considered in the risk-adjusted parcel of the objective function. Finally, the FEC decision would replace the right-hand side of the expression (17). The study of the properties related to this FEC is part of the authors' ongoing research.

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