A Tailored Derivative Instrument to Mitigate the Price-and-Quantity Risk faced by Wind Power Companies

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Abstract

The intermittent nature of wind generation combined with the well-known volatility of electricity spot prices expose Wind Power Companies (WPCs) committed to long-term forward contracts to the so-called price-and-quantity risk. Several instruments were designed in the past years to mitigate this risk exposure. However, most of them were mainly constructed to cope with only one of its parts, i.e., price or generation uncertainty. To tackle this issue, in this work, we propose a tailored derivative instrument for WPCs leveraging the principles of options and renewable indexes. The effectiveness and attractiveness of the proposed instrument, referred to as the Wind-Indexed Option (WInd-Op), are evaluated with real data from the Brazilian sector through a general equilibrium setup. We show that Solar Power Companies (SPCs) can be relevant candidates to back these derivatives. Additionally, when compared to the traditional put-and-call options as a benchmark, results indicate that the equilibrium obtained with the new derivative exhibits a significantly higher traded volume (2.9 times greater), lower premium prices (54.7% lower), and greater welfare gain (2.7 greater).

Keywords: Economic Equilibrium; Electricity Markets; Financial Derivatives; Risk Management; Renewable Energy; Wind Power Index.

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1. Introduction

The ever-increasing penetration of variable Renewable Energy Sources (vRES) – e.g., solar and wind power plants – in the current electrical generation mix introduce high levels of uncertainty and complexity to the energy portfolio management process of both generation companies and system operators due to their intermittent nature and limited production predictability [1]. On top of this supply uncertainty, from an economic perspective, spot prices for electricity in most power markets around the globe are recognized by their high variability and volatility [2]. In this context, the decarbonization agenda has driven power systems worldwide towards a massive transition from conventional to renewable generation fleet. This transition towards a zero-marginal cost and intermittent generation fleet imposes not only operational but also relevant economic and regulatory challenges (see [3] and [4]).

In Brazil, for instance, due to its hydro-dominated characteristic and centralized dispatch (by audited costs) with tight-pool-based price formation, the spot price recovers the day-ahead system's marginal cost based on a unit commitment software. This software uses exogenously calculated water values to balance the immediate and future opportunity costs of water, which are centrally calculated by the system operator through a chained set of dynamic programming-based dispatch planning models [5]. In this country, there is no real-time pricing, and deviations from the day-ahead unit commitment are directly charged to consumers through tariffs. According to its national system operator, the Brazilian system has a total installed capacity equal to 211 GW on October 2023, from which 51.4% is hydro, 17.3% is thermal – 8% gas, 2% oil, 7.3% biomass –, 12% is wind, 16% is solar – including distributed PV generation –, and the rest is composed by other sources including nuclear. However, the actual generation share of hydros is generally higher than 60%, which is partially used to compensate for almost all the wind and solar intermittency. Due to the massive participation of zero marginal cost renewable generation (hydro, wind, biomass, and solar generators) in the system (higher than 70% on average), spot prices are frequently at very low levels. Nevertheless, unexpected crises often break this pattern with high spot-price spikes due to several reasons, such as unforeseen droughts, planning bias [6], etc. As a consequence, a key aspect of the Brazilian power market is that generators often enroll in long-term power purchase agreements (PPA) [4], which are financial forward contracts.

The high reliance on forward contracts, which has promoted long-term electricity supply adequacy in Brazil over approximately two decades, was introduced in the 2004 regulatory reforms implemented in this country, when a new guideline requiring consumers to cover 100% of their annual consumption with forward contracts was passed. This ensured feasible and reliable project finance planning while mitigating the risk aversion of generation investors (on long periods of low spot prices) and consumers (on short periods of crises with very high spot prices). We refer the interested reader to [3] and [4]. In this context, the Brazilian power sector, albeit singular in its matrix composition, pricing formation, and regulatory framework, offers interesting insights for systems worldwide with an increasing share of zero marginal cost generation using forward contracts. Relevant evidence in favor of fixed-price forward contracts to address long-term supply adequacy in these contexts has been recently reported in [3], [4], and [7].

However, due to the intermittence of some renewable generation (e.g., wind and solar), they are exposed to mismatch (deficits and surpluses) with respect to their PPA, which may lead to the so-called Price-and-Quantity Risk (PQ-Risk) (see [8] and [9]). More specifically, this risk materializes in two specific states: 1) when there is a deficit in energy generation with respect to the contracted amount and the spot price is high, and 2) when there is a generation surplus and the spot price is low. In the former state, the generation incurs high expenses due to the clearing of the generation deficit on high spot prices. In the latter state, the surplus generation is cleared on very low spot prices, reducing the expected revenue. Thus, the PQ-Risk can be seen as a two-factor double-sided risk, i.e., it is based on two specific combinations (states) of two uncertainty factors (spot price and variable generation). In the past years, several instruments and approaches were introduced to electricity markets aiming at mitigating this risk exposure [8, 10–16].

Notably, most of the financial instruments were mainly built to cope with price or generation uncertainty, whereas most of the portfolio optimization approaches rely on capital-intensive or centrally coordinated portfolio structures. For instance, while in [8], a portfolio of complementary renewables is centrally coordinated to mitigate the PQ-Risk when selling a long-term forward contract, in [11], a renewable pool is proposed, and the quotas of future revenue streams are allocated according to a cooperative game approach. These approaches rely on a central party for synergy and risk-mitigation coordination. However, in [10], derivatives (call and put options) are studied in a multistage environment, highlighting the benefits of the flexibility of these relevant instruments. This relevant work highlights the benefits of a hedging instrument that is triggered only in price-exposure situations, thereby being more efficient in addressing the price risk. Following this finding, [12] proposes to optimally adjust the portfolio levels of renewable sources with call and put options to hedge against the PQ-Risk exposure when selling forward contracts, thereby utilizing the classical derivatives that only depend on spot price to address the cases where low generation is observed in high spot price scenarios.

The use of derivative and index-driven instruments is also reported in the literature. In [17], a standardized contract underlying the capacity factors for the average German wind resource was studied to help Wind Power Companies (WPCs) to cope with weather-related uncertainties. The authors in [14] designed a standard option contract model based on a different index, a renewable energy price index, and used an Auto-Regressive Integrated Moving Average (ARIMA) framework to forecast the index's future dynamics. Similarly, weather derivatives are also studied as an efficient hedging mechanism to address the quantity risk faced by Solar Power Companies (SPCs). In the particular context of this source, payoffs are, in general, dependent on the levels of temperature or solar irradiation being higher or lower than an *a-priori*-defined threshold. In [15] and [16], different weather derivatives are discussed to provide hedging strategies for an SPC.

Despite the relevance of the aforementioned literature, their solution approaches are based on either the physical combination of assets with complementary production profiles or the acquisition of different instrument types that might not be effective in mitigating the exposure to the particular two-factor double-sided PQ-Risk. In fact, they are usually designed to act effectively on price or generation uncertainty. However, in the midst of the significant shift toward a renewable, intermittent, and zero-marginal cost-based generation fleet, the design of new products tailored to effectively address the PQ-Risk and allow renewables to increase their contracting involvement is key.

Therefore, the objective of this work is to propose a new tailored financial hedging instrument to aid Brazilian WPCs to efficiently mitigate their exposure to the double-sided PQ-Risk when committed to long-term forward contracts. To achieve this goal, we utilize the idea of renewable indices and financial derivatives to develop a new Wind-Indexed Option (WInd-Op) that accounts for both the spot price and generation quantity signals to trigger the option payment. In this context, the WInd-Op offers a more detailed payoff function of the spot price and quantity (generation) for contracted renewable generators if compared with standard call and put options.

More objectively, we first introduce a novel index called the Wind Power Performance Index (WPP-I), designed to measure production imbalances and generation risk factors. Then, we propose a new derivative that offers a payoff exclusively in price-and-quantity states where the PQ-Risk materializes, i.e., in situations where there is either a production deficit alongside a high spot price or a generation surplus accompanied by a low spot price. Additionally, the magnitude of the payment corresponds to the financial exposure in both states, thereby resulting in a tailored payoff to address the PQ-Risk. These are salient features of the proposed derivative that are not found in the standard call and put option benchmark. As a consequence, payments that do not necessarily reduce losses due to the PQ-Risk (in states where the spot price and the renewable generation are both high or low at the same time) are mitigated. In this context, it is expected that in the equilibrium, agents should internalize this benefit, and the proposed derivative would be negotiated by lower premium values in comparison to the benchmark. This would be consistent with the finance and risk literature, where more complex and complete hedging products should lead to market conditions with more efficient solutions [18].

To study the properties of the proposed derivative instrument in a competitive marketplace, we derive a mathematical programming-based problem to identify and study the maximum welfare equilibrium state. Two numerical experiments are conducted to showcase the effectiveness and attractiveness of the proposed WInd-Op using real data from the Brazilian power market. It is relevant to mention that the proposed model and ideas presented in this work may be applicable to other renewable sources. Nevertheless, to address objective and data-driven conclusions, we limit the scope of this paper to the analysis of the proposed WInd-Op derivative using relevant and representative data of the two renewable sources exhibiting the most prominent expansion rates and complementary generation profiles in Brazil, the wind and solar in the northeastern region of this country. In this context, as can be seen in Figure 1, wind and solar generation profiles in this region (one of the most relevant wind generation sites – for further details on the wind generation capacity and data, see [19]) exhibit a relevant complementary pattern. As per the size of the benefits that will be further presented in our second case study, results indicate that SPCs are relevant candidates to issue this derivative due to their usual hourly complementarity production profile to wind sources.

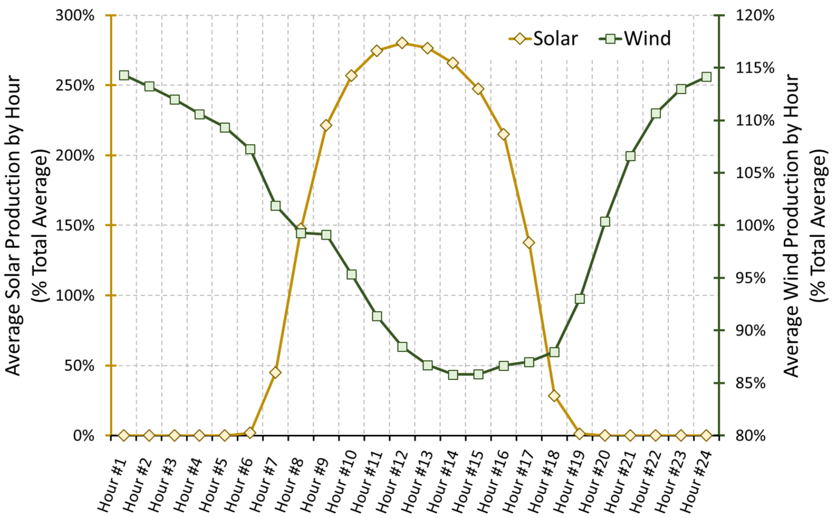

Figure 1: Hourly average generation profiles of typical wind and solar units in the northeastern area of Brazil in percentage of their historical average (historical records from 01-July-2019 up to 20-September-2021).

We also perform a numerical comparison with the traditional hedging strategy of acquiring put-and-call options to benchmark the performance of the proposed mechanism. Although tested with Brazilian data, the authors understand that the newly proposed ideas may be of interest to other power systems where long-term contracts are used as a long-term supply adequacy instrument. Therefore, the studies and insights provided in this paper may also contribute to fostering renewables competitiveness, reducing subsidies, and allowing natural complementary resources to address the PQ-Risk in other countries.

This paper is organized as follows. Section 2 presents the proposed financial hedge mechanism to protect WPP's revenues. In Section 3, the mathematical formulation for the risk-averse profit maximization problem to obtain the optimal contracting strategy for the proposed derivative by an individual producer is presented. Section 4 extends the mathematical formulation of Section 3 to a market equilibrium model. Section 5 provides numerical results for two case studies using real data from the Brazilian power sector. Conclusions are drawn in Section 6.

2. Supply Contracts backed on vRES and the Price-and-Quantity Risk

In this work, we consider a set $\mathcal{I} = \{1, \ldots, n\}$ of n vRES committed in long-term supply contracts with consumers (hereinafter referred to as a Power Purchase Agreement – PPA), with a fixed price (P_i) and volume (V_i). We assume that the PPA maturity of all vRES is larger than the analysis horizon represented by a set of T hours, namely, $\mathcal{T} = \{1, \ldots, T\}$. The revenue function, $f_i(\,\cdot\,)$, of a contracted renewable agent $i \in \mathcal{I}$ with an uncertain generation profile determined by the random vector $\tilde{\boldsymbol{G}}_i \triangleq \{\tilde{G}_{i,t}\}_{t \in \mathcal{T}}$, is given by

$$f_i\Big(P_i, V_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}\Big) = \sum_{t \in \mathcal{T}} \Big(P_i\, V_i + \Big(\tilde{G}_{i,t} - V_i\Big)\tilde{\pi}_t\Big), \tag{1}$$

where $\tilde{\boldsymbol{\pi}} \triangleq \{\tilde{\pi}_t\}_{t \in \mathcal{T}}$ stands for the random vector of energy spot prices for the whole horizon. In (1), the first term, $P_i\, V_i$, stands for the PPA fixed payment, whereas the second term, $(\tilde{G}_{i,t} - V_i)\tilde{\pi}_t$, represents the clearing in the spot price of the generation deficit or surplus with respect to the PPA volume. It should be noted that the revenue stream in expression (1) explicitly translates the aforementioned double-sided nature of the price-and-quantity risk due to a position in a long-term forward contract. In fact, while a high contracted volume increases the constant payments, it also increases the likelihood of a negative clearing in the short-term market. If, in a given scenario, a negative clearing is accompanied by a high spot price, the total revenue can be negative. Furthermore, on the other hand, if the renewable agent prefers to avoid a large exposition to the short-term market by contracting a low volume in the PPA, the likelihood of a generation surplus in comparison to the PPA amount is higher. In this context, however, the fixed parcel of the revenue is lower. Thus, if the former scenario has an associated low spot price realization, the overall revenue (fixed plus variable clearing in the short-term market) might not be enough to cover fixed expenses.

Therefore, although long-term supply contracts help in providing generators with more stable cash flows, in the case of renewable generators, with high uncertainty in the generation profile, it also exposes the agents to the PQ-Risk. The PQ-Risk materializes whenever one of these two aforementioned pairwise-linked scenarios occurs, i.e., generation deficit with a high spot price or generation surplus with a low spot price. In the next section, by targeting this specific double-sided nature of the PQ-Risk, we describe the proposed novel derivative instrument capable of efficiently mitigating the losses in the case of these events.

3. Wind-Indexed Option: Conceptual Design

Aiming to design a derivative instrument to reduce the negative impact of both sides of the previously discussed PQ-Risk, in this section, we describe the conceptual design of the proposed hedging instrument. Firstly, in Subsection 3.1, we establish its foundations, presenting a new *Wind Power Performance Index* (WPP-I). This index is one of the key components to trigger the derivative payoff. Then, in Subsection 3.2, the proposed derivative payoff function is described. Finally, in Section 3.3, we devise the overall net revenue stream of vRES when negotiating the proposed WInd-Op and their associated optimal willingness-to-contract curve.

3.1. Wind Power Performance Index (WPP-I)

Following the quantity risk dynamics discussed in Section 2, if $\tilde{\mathbb{G}}_t$ denotes a representative generation profile, e.g., for a given set of generators in a given region, at an hour $t \in \mathcal{T}$, and $F \in \mathbb{R}_+$ denotes an approximation to the total market amount of traded PPAs in this region, then, the WPP-I associated with this region can be defined as follows:

$$\Delta\big(\tilde{\mathbb{G}}_t, F\big) \triangleq \frac{\tilde{\mathbb{G}}_t}{F} - 1 \qquad \forall\, t \in \mathcal{T}. \tag{2}$$

Roughly speaking, the WPP-I definition in (2) highlights the deficit and surplus condition of a given wind power profile with respect to a reference of involvement in the forward market. Therefore, if at a given hour $t \in \mathcal{T}$, the index is positive – e.g., $\Delta\big(\tilde{\mathbb{G}}_t, F\big) > 0$, then it indicates that the generation in that region is in a surplus scenario with respect to the market reference of typical forward involvement. Analogously, if the index is negative at a given hour $t \in \mathcal{T}$ – e.g., $\Delta\big(\tilde{\mathbb{G}}_t, F\big) < 0$, then a generation deficit in that region is observed. It is worth highlighting that, in the case of a standardized instrument design, the generation profile $\big\{\tilde{\mathbb{G}}_t\big\}_{t\in\mathcal{T}}$ and the reference F should be of interest to a significant group of generation companies (e.g., the littoral of the Northeast Region of Brazil). Thus, they should be selected according to their representativeness, estimated according to transparent and audited processes, and made available to all market players. However, it can also be the case where specific contracts could be designed for specific companies through private bilateral instruments.

It is beyond the scope of this work to explore all possible formats of estimation processes that could be used to obtain representative generation profiles and the reference to the forward involvement amount. So, for the sake of conciseness and due to the limited scope of this paper, the indexology (the study, creation, maintenance, and analysis of financial indices) of the proposed Wind Power Performance Index is not discussed in this work and is suggested as a relevant future research topic. Notwithstanding, we understand the diversity of possible ways that these two elements composing the proposed WPP-I can be estimated as a salient feature of the concept. This diversity may enable market agents interested in creating these products to compete for the attractiveness of their own indexes. For instance, if one has a now-casting estimation process that better estimates the term $\frac{\tilde{\mathbb{G}}_t}{F}$ for a given set of relevant wind power generators, this agent should generate a more representative WPP-I. In the case study, we test the proposed concept with a practical approach and discuss further possible extensions as future work in the conclusions section. Next, based on the concept of WPP-I defined in this section, we present the proposed hedging instrument.

3.2. WInd-Op Revenue Function

The proposed WInd-Op is built only to trigger a payoff against the two pairwise-linked events (discussed in Section 2) related to the PQ-Risk: (i) a deficit in production with a high spot price, and (ii) a surplus in production with a low spot price. In order to define what is low and high, a reference price S, similar to the strike price of call and put options, is used. Therefore, based on the surplus or deficit amounts, defined by WPP-I, and on the difference between the spot and the reference price, we can define the payoff function of the holder (buyer) with q MWh of the proposed derivative for any period (hour) t within the maturity horizon $\mathcal{T}$ as follows:

$$\Gamma\Big(q_i, \tilde{\mathbb{G}}_t, \tilde{\pi}_t\Big) = \Big(\max\Big\{(S - \tilde{\pi}_t)\Delta\big(\tilde{\mathbb{G}}_t, F\big), 0\Big\} - \lambda\Big)q_i. \tag{3}$$

The first term of expression (3) refers to the payoff of the proposed WInd-Op. The product between the WPP-I and the strike and spot difference highlights the essential dynamics of the WInd-Op to efficiently tackle the double-sided facet of the PQ-Risk by securitizing an amount q_i (in average MW) if both spot price and energy production are against the holder.

On one side, if, at the same time, $t \in \mathcal{T}$, $\Delta\big(\tilde{\mathbb{G}}_t, F\big) < 0$, i.e., there is a deficit in generation with respect to the forward involvement reference, and $\big(S - \tilde{\pi}_t\big) < 0$, i.e., the spot price is higher than the strike price, then the holder has the right to exercise the option. In this case, the holder receives a financial payoff equal to $\Big[\big(S - \tilde{\pi}_t\big)\,\Delta\big(\tilde{\mathbb{G}}_t, F\big)\Big]\, q_i$, which may be closely related to its incurred financial loss if its generation profile and forward involvement are reasonably well approximated by $\mathbb{G}_t$ and F. Note that, in this scenario, the payoff function indicates that the agent is buying the generation-adjusted amount $\Delta\big(\tilde{\mathbb{G}}_t, F\big)q_i$ of energy at the *a priori*-specified strike price S and selling it back in the short-term market by a higher value at the spot price $\tilde{\pi}_t$. This payoff is equivalent to the payoff of a *call option* with a stochastically adjusted delivery amount equal to $\Delta\big(\tilde{\mathbb{G}}_t, F\big)q_i$.

On the other side, if, at the same time, $t \in \mathcal{T}$, $\Delta\big(\tilde{\mathbb{G}}_t, F\big) > 0$ (i.e., a generation surplus with respect to the forward involvement reference) and $\big(S - \tilde{\pi}_t\big) > 0$ (a lower spot price with respect to the strike price reference), then the holder has the right to exercise the option, receiving a financial payoff equal to $\Big[\big(S - \tilde{\pi}_t\big)\,\Delta\big(\tilde{\mathbb{G}}_t, F\big)\Big]\, q_i$, to compensate the lower income for the generation surplus. Hence, the payoff indicates that the agent is buying the generation-adjusted amount $\Delta\big(\tilde{\mathbb{G}}_t, F\big)q_i$ of energy in the short-term market at a spot price $\tilde{\pi}_t$ to sell it at the higher *a priori*-specified strike price S. In this scenario, the derivative has a payoff equivalent to the payoff of a *put option* with a stochastically-adjusted clearing amount equal to $\Delta\big(\tilde{\mathbb{G}}_t, F\big)q_i$.

In Figure 2, we showcase the payoff of the proposed WInd-Op for a given strike price $S = 90$ \$/MWh as a function of the spot price for different realizations of the WPP-I. For illustrative purposes, we disregard the premium component, i.e., $\lambda = 0$ \$/MWh. It is remarkable the similarity of the payoff function with the standard put-and-call option combination. It is worth noticing that for the particular events where a 100% surplus or deficit is observed, i.e., $\big|\Delta\big(\tilde{\mathbb{G}}_t, F\big)\big| = 1$, it recovers exactly the standard combined put-and-call option payoff function; with $\Delta\big(\tilde{\mathbb{G}}_t, F\big) = 1$ triggering the call option side and $\Delta\big(\tilde{\mathbb{G}}_t, F\big) = -1$ triggering the put option. Nevertheless, according to the proposed derivative payoff function (3), different scenario realizations of $\Delta\big(\tilde{\mathbb{G}}_t, F\big)$ lead to distinct payoff amounts. For instance, the red lines show the payoff of the call option side of the proposed derivative adjusted by the different levels of the WPP-I value $\Delta\big(\tilde{\mathbb{G}}_t, F\big)$. Similarly, the blue lines indicate the adjusted put option payoff side.

It is important to highlight that the payoff ($\Gamma(\cdot)$) of the proposed WInd-Op tends to be lower than the standard put-and-call option combination, which better accommodates the holder's needs to hedge the PQ-Risk. As a consequence, we argue that the proposed instrument is a more fit-for-purpose derivative than the standard call-and-put options, thereby providing a more efficient hedging instrument for the PQ-Risk exposure of WPCs operating in a competitive electricity market. In our case study, we showcase that in the equilibrium, the proposed derivative is cheaper and more effective in increasing the total social welfare than the standard put-and-call option benchmark.

3.3. Optimal Willingness-to-Contract Curve

The overall net revenue of a given contracted vRES $i \in \mathcal{I}$ buying the proposed derivative (with $q_i \geq 0$ representing the acquisition of the derivative) can be represented by combining the PPA revenue expression (1) with the payoff function of the instrument (3) as follows:

$$R_i(\lambda, q_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}) = \sum_{t \in \mathcal{T}} \left[P_i\, V_i + \Big(\tilde{G}_{i,t} - V_i\Big)\tilde{\pi}_t \; + \Big(\max\Big\{ \big(S - \tilde{\pi}_t\big)\, \Delta\big(\tilde{\mathbb{G}}_t, F\big),\, 0 \Big\} - \lambda \Big) q_i \right]. \tag{4}$$

It is worth highlighting that, under the occurrence of the PQ-Risk triggering events (those in which the proposed derivative is exercised), under certain conditions, a specifically designed instrument can fully immunize this agent's net revenue against the spot-price risk factor. This result is formalized next in **Theorem 1**.

Theorem 1. *Assume a WPC $i \in \mathcal{I}$ committed to a long-term PPA with an associated sale price and volume given by P_i and V_i, respectively. Furthermore, consider a WInd-Op that is designed over the*

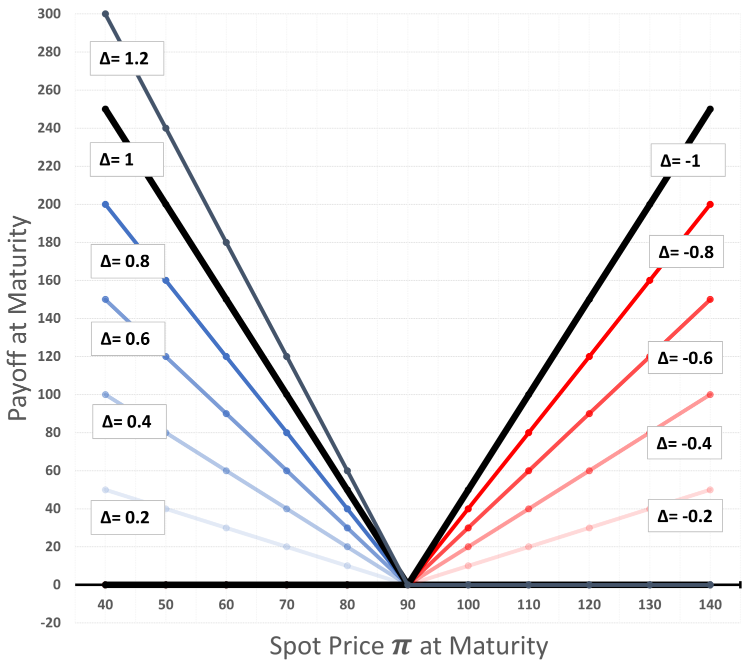

Figure 2: Payoff function, $\Gamma(\cdot)$, of the proposed instrument for a strike price $S = 90$ \$/MWh, null premium ($\lambda = 0$ \$/MWh), and different values of the WPP-I.

production profile and forward involvement of the WPC, i.e., $\tilde{\mathbb{G}}_t = \tilde{G}_{i,t},\ \forall\ t \in \mathcal{T}$ *and* $F = V_i$, *and the strike price is equal to the PPA price, i.e.,* $S = P_i$. *If the WPC buys the total PPA amount in this WInd-Op, i.e.,* $q_i = V_i$, *then, under the occurrence of the PQ-Risk triggering events (those in which the proposed derivative is exercised), the revenue function* (4) *of the WPC resumes to*

$$R_i(\lambda, F, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}) = \sum_{t \in \mathcal{T}} \Big(P_i\, \tilde{G}_{i,t} - \lambda F \Big), \tag{5}$$

i.e., the spot-price risk factor vanishes from the revenue expression.

Proof. Firstly, for a given hour $t \in \mathcal{T}$ along the maturity of the derivative, under the assumptions that $\tilde{\mathbb{G}}_t = \tilde{G}_{i,t},\ \forall\ t \in \mathcal{T}$, $q_i = V_i = F$, $S = P_i$, and that we are found in an event associated with the PQ-Risk, where the derivative payment is triggered, the net revenue of the referred WPC is given by

$$R_i(\lambda, q_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}) = P_i\, F + \Big(\tilde{G}_{i,t} - F\Big)\tilde{\pi}_t\ + \Big(\big(P_i - \tilde{\pi}_t\big)\, \Delta\big(\tilde{G}_{i,t}, F\big) - \lambda \Big) F.$$

By using the definition of the WPP-I in (2), we have that

$$R_i(\lambda, q_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}) = P_i\, F + \Big(\tilde{G}_{i,t} - F\Big)\tilde{\pi}_t\ + \left(\big(P_i - \tilde{\pi}_t\big) \left(\frac{\tilde{G}_{i,t}}{F} - 1 \right) - \lambda \right) F = \tilde{G}_{i,t}\, P_i - \lambda F.$$

Finally, by summing along the hours of analysis $t \in \mathcal{T}$,

$$R_i(\lambda, F, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}) = \sum_{t \in \mathcal{T}} \Big(P_i \, \tilde{G}_{i,t} - \lambda F \Big).$$

□

Theorem 1 formalizes two important aspects of the proposed derivative instrument. Firstly, the theorem holds under the hypothesis of $\tilde{\mathbb{G}}_t = \tilde{G}_{i,t}, \; \forall \; t \in \mathcal{T}, \; q_i = V_i = F$, and $S = P_i$. Thus, it states that if the instrument is designed over the production profile of the WPC, the WInd-Op significantly reduces the PQ-Risk of the WPC induced by its uncertain generation when involved in long-term PPAs. As the natural hedge, in the absence of the proposed instrument, is to reduce the forward involvement, the newly proposed derivative should induce higher forward involvements, allowing more long-term contracts to be negotiated in the market by WPCs. Secondly, under the hypothesis that an event in which the instrument is exercised (i.e., a context in which the WPC is exposed to the PQ-Risk), the proposed derivative aims to recover only the losses incurred by the WPC, avoiding extra payments that would be recovered by the premium payment in a market equilibrium situation. So, the proposed derivative is efficient in reducing WPCs losses when selling long-term forward contracts.

Finally, in order to fully explore the proposed instrument value, each economic agent should pursue a trading strategy that optimizes its risk-adjusted wiliness-to-contract in the WInd-Op given its premium λ. Formally, let ρ_{θ_i} to stand for a θ_i-parameterized coherent risk measure functional that better characterizes the attitude towards risk of a given vRES $i \in \mathcal{I}$ when negotiating the proposed derivative instrument. Then, for a given premium λ, the decision-making problem that defines the optimal amount of the proposed instrument that a renewable agent $i \in \mathcal{I}$ is willing to contract is given by

$$q_i^* \left(\lambda\right) \in \underset{\underline{q}_i \leq q_i \leq \overline{q}_i}{\arg\max} \left\{ \rho_{\theta_i} \left(R_i \Big(\lambda, q_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}} \Big) \right) \right\}. \tag{6}$$

In (6), $\underline{q}_i$ and $\overline{q}_i$ stand for the minimum and maximum contracting levels, respectively. So, it is important to note that if $q_i \geq 0$, it means that agent i is willing to buy the derivative, whereas if $q_i \leq 0$, it means that agent i is willing to sell it. So, by means of a given selection of the bounds, $\underline{q}_i$ and $\overline{q}_i$, we can either define buyers (selecting value such that $\underline{q}_i = 0$ and $\overline{q}_i \geq 0$) and sellers (with $\underline{q}_i \leq 0$ and $\overline{q}_i = 0$), or let agents free to select their role (selecting value such that $\underline{q}_i \leq 0$ and $\overline{q}_i \geq 0$).

4. Economic Equilibrium and Market Model

In this section, we outline the setup to study the properties and effectiveness of the proposed WInd-Op when traded in a competitive marketplace. Roughly speaking, we evaluate the performance of the proposed derivative within an *economic equilibrium*, i.e., within a state of the market in which both willingness-to-supply and willingness-to-consume are balanced among all participants. Formally, for a given premium λ, an economic equilibrium happens whenever

$$\sum_{i\in\mathcal{I}} q_i^*\big(\lambda\big) = 0, \tag{7}$$

with $q_i^*\big(\lambda\big)$ defined as in (6). Following the standard economic literature and uniform pricing theory, a price-taker economic equilibrium state of a competitive market can be found by means of solving the following maximum welfare problem:

$$\boldsymbol{q}^* \in \underset{\{q_i\}_{i\in\mathcal{I}}}{\arg\max} \; \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}} \left[P_i\, V_i + \rho_{\theta_i}\bigg(\Big(\tilde{G}_{i,t} - V_i\Big)\tilde{\pi}_t + \max\Big\{ \big(S - \tilde{\pi}_t\big)\, \Delta\big(\tilde{\mathbb{G}}_t, F\big),\; 0\Big\}\, q_i \bigg) \right] \tag{8}$$

subject to:

$$\sum_{i\in\mathcal{I}} q_i = 0 \tag{9}$$

$$\underline{q}_i \leq q_i \leq \overline{q}_i, \qquad \forall\, i \in \mathcal{I}. \tag{10}$$

The maximum welfare problem (8)–(10) is obtained by jointly maximizing the risk-adjusted revenue of all players, as per (6), considering the equilibrium constraint (7). The *equilibrium premium* $\big(\lambda^*\big)$ for the proposed instrument can be computed by solving problem (8)–(10) and evaluating the dual variable of constraint (9). In fact, it recovers the marginal impact in the overall market welfare (among all participants), similar to the standard uniform pricing framework [20]. Furthermore, the associated solution $\boldsymbol{q}^* \triangleq \{q_i^*\}_{i\in\mathcal{I}}$ for (8)–(10) is a best-response contracting level for each renewable agent $i \in \mathcal{I}$ to the WInd-Op equilibrium premium λ^*, i.e., the optimal $q_i^*\big(\lambda^*\big)$ as in (6). In the next section, we present two numerical studies to illustrate the effectiveness and attractiveness of the proposed instrument using real data from the Brazilian power system.

5. Numerical Experiment

In this section, we illustrate the effectiveness of the proposed WInd-Op by means of two case studies using real data from the Brazilian power sector. The dataset for the two case studies is available at [21]. In the first one, the equilibrium between a single WPC (buyers) and three SPCs (sellers) is considered. In this case, we assume a "bilateral" trading environment where the derivative is conceived by the single buyer to specifically hedge its PQ-Risk, i.e., the WPP-I is based on the forward involvement and generation profile of the specific buyer. In the second case study, a wider trading environment is considered, with multiple WPCs (buyers) and SPCs (sellers). In this case, the derivative is based on the average generation profile and forward involvement of a subset of WPCs from a specific state (Bahia) of the northeastern region of Brazil to analyze the derivative performance within a more realistic setting. Additionally, it is well-known that forward contract details such as contract prices constitute sensitive private information and are always being updated according to new market circumstances. Thus, in order to promote meaningful analyses and provide relevant evidence regarding the performance of the proposed derivative as a hedging instrument, we assume, in both case studies, that generators are contracted at 192 \$/MWh, the expected value of the average spot price within the study horizon, and that the strike price of the proposed derivative is equal to the forward price, i.e., $S = 192$ \$/MWh. In this setting, in our analyses, the forward market is in neutral equilibrium with the spot market, i.e., it is not interfering with the expected revenue of generators [13], and the new product strike price meets the forward market conditions; thereby, the proposed derivative is tested for the reference price in which generators are contracted.

In both case studies, we analyze the benefits introduced by the proposed instrument and benchmark it with the traditional put-and-call options to evaluate its performance. Formally, in the context of this work, for a given amount z_i of put-and-call option negotiated by a renewable agent $i \in \mathcal{I}$, the payoff function at a given hour $t \in \mathcal{T}$ within the maturity of analysis is given by

$$\left(\max \left\{ \big(S - \tilde{\pi}_t\big), \big(\tilde{\pi}_t - S\big) \right\} - \mu \right) z_i, \tag{11}$$

with S and μ representing the put-and-call option strike price and premium, respectively. It is thus noteworthy that the benchmark derivative features an exercise rule and associated payoff function, which solely rely on the prevailing spot price conditions.

Finally, it is relevant to mention that in the next sections, we provide empirical results and conclusions that are only valid within the scope of the selected hypotheses, data, and metrics.

5.1. Risk aversion and scenario generation

To characterize each renewable agent's attitude towards risk, we consider in both case studies a convex combination between the *Expected Value* of the net revenue stream (4) and the left-tail, α-quantile-based risk functional known as the *Conditional Value-at-Risk* (CVaR_α) (see [22]). More specifically, for each renewable agent $i \in \mathcal{I}$, let $\theta_i \triangleq \{\alpha_i, \beta_i\}$ with $\beta_i \in [0, 1]$ and $\alpha_i \in (0, 1]$. Then, the θ_i-parameterized (coherent) risk functional measure (ρ_{θ_i}) considered in this numerical experiment is defined as follows:

$$\rho_{\theta_i}\big(\tilde{R}_i\big) = \beta_i \, \text{CVaR}_{\alpha_i}\big(\tilde{R}_i\big) + \big(1 - \beta_i\big) \, \mathbb{E}\big[\tilde{R}_i\big]. \tag{12}$$

In (12), both α_i and β_i play the role of risk-averse parameters for the renewable agent $i \in \mathcal{I}$. The former (α_i) stands for the confidence level of the CVaR measure, indicating the $(1 - \alpha_i)$-quantile up to which the worse net revenues scenarios are averaged. The latter (β_i), on the other hand, balances the weight given to the CVaR measure against the Expected Value. From a risk attitude perspective, according to [22], (12) can be interpreted as a Certainty Equivalent functional that assigns a monetary value to a given cash flow. Therefore, an economic agent $i \in \mathcal{I}$ whose risk attitude is well-represented by ρ_{θ_i} aims to select the best amount of WInd-Op by maximizing this functional. Note that the risk measure (12) is general enough to map a variety of risk profiles. In fact, if the renewable agent is Risk Neutral, then it can be characterized by setting $\beta_i = 0$, meanwhile increasing the value of β_i induces stronger levels of risk-aversion attitude. For expository purposes, we consider in both case studies $\alpha_i = 0.95,\ \forall\ i \in \mathcal{I}$, and vary only the parameter β_i.

Regarding the scenarios and probabilities used to characterize the uncertainties, we assume that the WInd-Op maturity spans a whole week, $\mathcal{T} = \{1, \ldots, 168\}$, with WPP-I associated with the generation of the wind farm. To characterize the uncertain factors within the study horizon, we follow the standard stochastic modeling approach and assume a probability space $\big(\Omega, \mathcal{F}, \mathbb{P}\big)$ with a finite sample set (plausible scenarios). A pure data-driven (non-parametric) decision-making approach is considered by assigning to the set of scenarios a collection of chronologically coherent historical data with an empirical probability mass equal to $1/|\Omega|$ assigned to each scenario. The scenario data are generated using observed weeks of hourly energy production for all renewable power plants considered in each case study and the energy spot prices for the Northeast (NE) Region of the Brazilian system. The data was extracted from July 2019 up to July 2021, resulting in a total of 104 representative weeks of renewable and spot price scenarios, preserving both cross and temporal dependencies.

Under the above conditions, i.e., CVaR-based preference functions as (12) and discrete sample space, the equilibrium problem (8)–(10) can be conveniently reformulated as a linear programming problem. For the sake of brevity, we omit the formulation. For the interested reader, we refer to the [23] as the paper proposing the CVaR reformulation as a linear optimization problem and to [12] and [24] for electricity market applications using the same reformulation. Within this context, the solution of the equilibrium problem for both case studies was implemented in *Julia Language*, using JuMP [25]. The source code is available under request.

5.2. Case Study I: Single WPC

In Table 1, all details of each renewable power plant considered in this Case Study I are presented. Column 1 and Column 2 indicate, respectively, the name of the power plants and their source type; Column 3 and Column 4 present, respectively, the PPA volume (average MW) and sales price (\$/MWh) of each renewable agent; Column 5 and Column 6 display the minimum and maximum amount that each agent is able to negotiate; Column 7 depicts the risk-averse level of each power company; and Column 8 displays the region in which each agent is located. Note that to correctly characterize the trading environment in which the WPC is the holder (buyer) of the derivative and the SPCs are the underwriters (sellers), the minimum level for the former and the maximum level for the latter are set to zero. Also, for illustrative purposes, we assume that each SPC has different attitudes towards risk, with *Lapa* exhibiting a low risk-averse level, *São Pedro* with a medium risk-averse level, and *Bom Jesus* with a high risk-averse level.

Table 1: Data and details of each renewable power plant considered in this Case Study I.

Power Plant	Source	V	P	$\underline{q}$	$\overline{q}$	β	Region
Brotas de Macaúbas	Wind	35.7	192	0.0	35.7	0.95	NE
Lapa	Solar	17.0	192	-17.0	0.0	0.10	NE
São Pedro	Solar	16.0	192	-16.0	0.0	0.50	NE
Bom Jesus	Solar	16.8	192	-16.8	0.0	0.90	NE

In Figure 3, the willingness-to-contract curve for the WPC (demand curve) and the aggregated willingness-to-contract curve for the SPCs (offer curve) are presented, with the intersection between demand and offer curves indicating the equilibrium for the premium[2]. Firstly, note that the supply (selling) curve starts at (roughly) 45 \$/MWh and follows the risk-averse profile of each solar power company. More specifically, the SPC with the lowest risk-averse level, *Lapa* (in orange), comes first in the "merit order", followed by *São Pedro* (in green) and *Bom Jesus* (in pink). Furthermore, from the buying counterpart (in blue), the maximum price the WPC is willing to buy the instrument is close to 100 \$/MWh. The equilibrium premium is settled at $\lambda^* = 78$ \$/MWh. We highlight that these values are significantly below the PPA sales price (192 \$/MWh). Thus, the derivative can be classified as a relatively cheap product for trading.

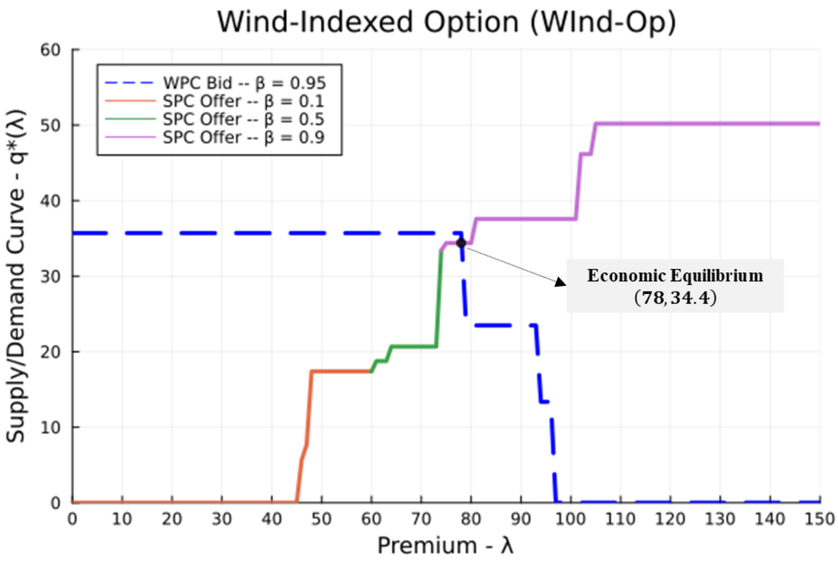

Figure 3: WPC's willingness-to-demand curve and the SPCs' willingness-to-supply curves for the proposed WInd-Op.

To illustrate the benefits of the proposed WInd-Op, in Table 2, we display the premium at equi-

[2]We refer to [26] for further discussion, formal analysis, and interpretation related to, economic equilibrium, uniform pricing, and willingness-to-contract curves.

librium (Column 2), the contracting level of each renewable company (Column 3), and the variation of the Expected Value (Column 4), CVaR (Column 5), and Certainty Equivalent (Column 6) with respect to not trading the hedging instrument (thus committed only in the long-term contract). Firstly, note that, in the equilibrium, all renewable companies increase their certainty equivalent metrics with respect to the context of not trading the hedging instrument, indicating an increase in the overall welfare value. In this context, all agents, according to their risk profiles, are better off in the case where they can trade the proposed derivative. We highlight that the CVaR metric for the WPC (buyer counterpart) improved against a decrease in the Expected Value, whereas the reverse condition is observed for all SPCs. This happens because the buyer, who is purchasing a hedging instrument, does so to reduce risk, thereby seeking a better risk metric in exchange for a fixed payment, which decreases the expected value. On the other hand, sellers are adding to their revenue function a negative payoff, which was set by the equilibrium to cover the PQ-Risk by maximizing total welfare. So, it is expected that their risk would increase, yet only at a given price (premium) that compensates in terms of their certainty equivalent. So, the obtained equilibrium satisfies both the willingness to hedge of the buyers and the expected gain of the sellers as a reward.

Table 2: Equilibrium results for the proposed derivative and relative performance metrics with respect to not trading the derivative

Power Plant	$\boldsymbol{\lambda}^*$	$\boldsymbol{q}^*$	$\Delta\mathbb{E}$	ΔCVaR	$\Delta\rho$
Brotas de Macaúbas	78.0	34.0	$-213,978$	$81,260$	$66,498$
Lapa	78.0	-17.0	$108,268$	$-64,275$	$91,014$
São Pedro	78.0	-16.0	$99,557$	$-61,457$	$19,050$
Bom Jesus	78.0	-1.0	$6,152$	-42	577

Finally, in order to evaluate the effectiveness of the proposed product, we benchmark the equilibrium results with another equilibrium where we replace the proposed derivative with the standard put-and-call option. Table 3 displays the same result structure compared to Table 2, but for the standard put-and-call option, with μ^* representing the premium of the derivative and $\boldsymbol{z}^*$ the respective amount traded at equilibrium. Firstly, note that, in the benchmark equilibrium, the total volume traded in standard put-and-call options (Column 3 of Table 3) is significantly lower than the volume traded in the proposed WInd-Op (Column 3 of Table 2). This happens because the standard derivative delivers a payoff proportional to the full amount contracted, q_i, whereas the proposed derivative delivers only the parcel of q_i under the PQ-Risk, i.e., q_i is adjusted by $\Delta\big(\tilde{\mathbb{G}}_t, F\big)$. Additionally, the put-and-call option premium at equilibrium (Column 2 of Table 3) is higher when compared to the premium at the equilibrium of the proposed instrument (Column 2 of Table 2), indicating a higher hedging cost in the benchmark case. Furthermore, the increase in the Certainty Equivalent level (Column 6 of Table 3) of all renewable companies is lower when compared to the WInd-Op (Column 6 of Table 2), except for the SPC with the highest risk-aversion level (*Bom Jesus*) which had a slightly superior increase, which indicates that the proposed derivative provides higher gains to the buyers and inframarginal sellers in comparison to the benchmark. These results indicate that, by adjusting the payoff according to a representative volumetric index, the proposed derivative is capable of reducing the hedging cost, increasing the market liquidity, and improving the benefits for most of the market players (buyer and inframarginal sellers).

Table 3: Equilibrium results for a standard put-and-call option and relative performance metrics with respect to not trading the option

Power Plant	$\boldsymbol{\mu}^*$	$\boldsymbol{z}^*$	$\Delta\mathbb{E}$	ΔCVaR	$\Delta\rho$
Brotas de Macaúbas	124.0	15.0	$-43,783$	$36,757$	$32,730$
Lapa	124.0	-13.0	$39,376$	$-232,460$	$12,193$
São Pedro	124.0	-1.0	$2,184$	$-1,461$	361
Bom Jesus	124.0	-1.0	$2,223$	917	$1,047$

5.3. Case Study II: Multi-vRES Market

In this second case study, the attractiveness of the proposed instrument is evaluated in a wider environment comprising 26 agents, namely, 15 WPC and 11 SPC. In Table 4, the specific data and details for each renewable power plant considered in this case study are presented. Column 1, Column 2, and Column 3 indicate the name of each power plant, the source type, and the individual firm energy certificates (FEC)[3], respectively; Column 4 and Column 5 express, respectively, the PPA volume and sales price due to each renewable agent. We assume a long-term contracting level equal to 90% of the FEC of each agent and the forward price equal to the expected value of the average spot price during the contract horizon, as motivated at the beginning of Section 5. Column 6 and Column 7 display the minimum and maximum amount of the instrument each vRES is able to negotiate (defined as the FEC, which is also the maximum regulatory forward contracting limit); Column 8 presents the risk-averse level of each power company; and Column 9 and Column 10 display, respectively, the State and Region the vRES are located. Note that, similar to Case Study I (Section 5.2), we also assume that the SPCs are the sellers of the WInd-Op; thus, their maximum trading levels are set to zero. Nevertheless, in this case study, we relax the condition over the WPCs and allow them to both buy and sell the derivative. Furthermore, for illustrative purposes, we consider that each SPC has different attitudes towards risk, with risk parameters displayed in Column 8 of Table 4.

In this case study, the WPP-I is written over public data from WPCs in the state of Bahia, NE of Brazil. So, in this case study, the spot price remains the same as in the previous one, but the WPP-I reflects the overall wind power production of the 21 power plants already in operation in the state of Bahia (state of the NE region of Brazil). To emulate a realistic case where the total PPA

[3]FECs are issued to each power plant in Brazil by the Ministry of Mines and Energy and, for the purposes of this paper, it is considered as the maximum regulatory contracting amount. See [4] for further details.

Table 4: Data and details of each renewable power plant

Power Plant	Source	FEC	V	P	$\underline{q}$	$\overline{q}$	β	State	Region
Brotas de Macaúbas	Wind	35.70	32.13	192.00	$-$ 35.70	35.70	0.95	BA	NE
Calango 1	Wind	27.80	25.02	192.00	$-$ 27.80	27.80	0.95	RN	NE
Calango 2	Wind	40.00	36.00	192.00	$-$ 40.00	40.00	0.95	RN	NE
Chapada I	Wind	110.00	99.00	192.00	$-$110.00	110.00	0.95	PI	NE
Curva dos Ventos	Wind	27.70	24.93	192.00	$-$ 27.70	27.70	0.95	BA	NE
Caetés II	Wind	95.00	85.23	192.00	$-$ 94.70	94.70	0.95	PE	NE
Pelourinho	Wind	23.60	21.24	192.00	$-$ 23.60	23.60	0.95	BA	NE
Serra de Santana 1 e 2	Wind	47.30	42.57	192.00	$-$ 47.30	47.30	0.95	RN	NE
Serra de Santana 3	Wind	52.50	47.25	192.00	$-$ 52.50	52.50	0.95	RN	NE
Cristal	Wind	47.70	42.93	192.00	$-$ 47.70	47.70	0.95	BA	NE
Caetité 123	Wind	38.90	35.01	192.00	$-$ 38.90	38.90	0.95	BA	NE
Brisa Potiguar I	Wind	89.40	80.46	192.00	$-$ 89.40	89.40	0.95	RN	NE
Pedra Cheirosa	Wind	27.50	24.75	192.00	$-$ 27.50	27.50	0.95	CE	NE
Trairí	Wind	97.20	87.48	192.00	$-$ 97.20	97.20	0.95	CE	NE
Icaraizinho	Wind	20.80	18.72	192.00	$-$ 20.80	20.80	0.95	CE	NE
Lapa	Solar	17.00	15.66	192.00	$-$ 17.40	0.00	0.30	BA	NE
São Pedro	Solar	16.00	14.40	192.00	$-$ 14.40	0.00	0.50	BA	NE
Juazeiro Solar	Solar	34.80	31.32	192.00	$-$ 31.32	0.00	0.70	BA	NE
Bom Jesus	Solar	17.00	15.12	192.00	$-$ 16.80	0.00	0.30	BA	NE
Horizonte	Solar	25.00	22.05	192.00	$-$ 24.50	0.00	0.50	BA	NE
Ituverava	Solar	58.80	52.92	192.00	$-$ 58.80	0.00	0.70	BA	NE
Calcário	Solar	35.00	31.32	192.00	$-$ 34.80	0.00	0.30	CE	NE
Nova Olinda	Solar	61.60	55.44	192.00	$-$ 61.60	0.00	0.50	PI	NE
Assú V	Solar	9.20	8.28	192.00	$-$ 9.20	0.00	0.70	RN	NE
Floresta	Solar	25.00	22.59	192.00	$-$ 25.10	0.00	0.30	RN	NE
Sol do Futuro	Solar	16.00	14.58	192.00	$-$ 16.20	0.00	0.50	CE	NE

volume would not be precisely calibrated to a given WPC, we build the WPP-I with the forward involvement reference F equal to the overall FEC amount of the 21 power plants comprising the generation profile. Additionally, to add another layer of reality, we considered an instance where not all generators composing the generation index participate in the equilibrium, and we also permit other generators from the NE region to participate. This scenario explores an interesting reality in which the WPP-I would not be perfectly designed for any generator buying the derivative, but in the equilibrium, the attractiveness of the proposed derivative will be reflected by each generator traded amount and the equilibrium price. Figure 4 showcases the WPP-I hourly distribution over the week of which the derivative is valid. We highlight the seasonal-like dynamics of the index, typically observed in wind production worldwide: a high generation level during the night followed by a decrease in production in daylight periods.

The general equilibrium results and relative gain metrics (benefits compared to the base case, where WInd-Op is not available and agents' revenues are based only on the forward and spot markets) are presented in Table 5. This table follows Table 2, with additional percentage information about

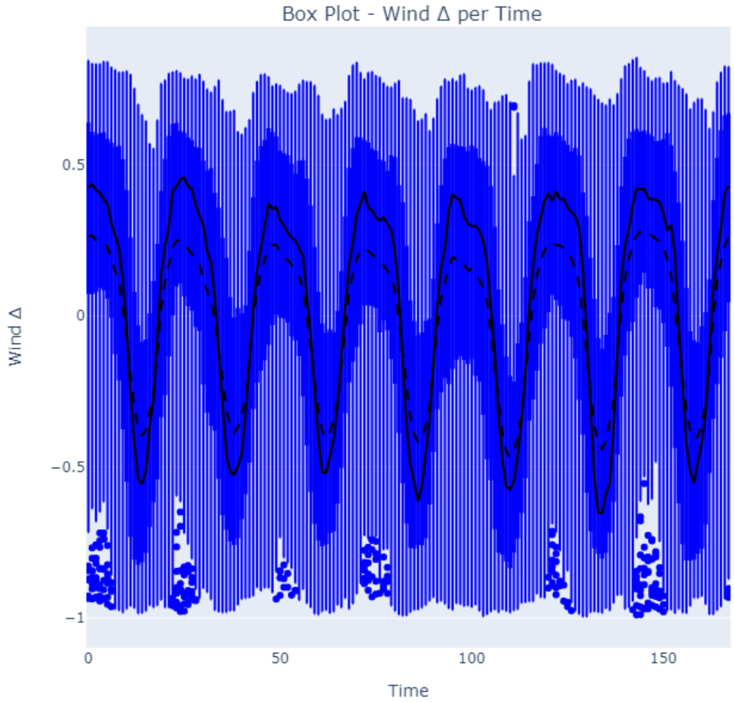

Figure 4: WPP-I hourly distribution over the week (derivative horizon).

the traded amounts with respect to the FEC of each unity and certainty equivalent variation. First, we highlight the existence of an equilibrium in this market between wind and solar companies with a total of 355.00 avgMW negotiated at an equilibrium premium of 66.00 R$/MWh. Furthermore, we observe an increase in each agent's certainty equivalent level with respect to the base case, thus indicating the attractiveness of this hedging instrument for the selected set of agents. Note that we are excluding many other actors that could be participating, such as trading companies, hydro generators, and banks, just to mention a few. In fact, note that its measured benefits can reach values higher than 100% (e.g., *Brotas de Macaúbas* and *Calango*) with an increase of 281% for *Caetité 123*. An increase in the CVaR level is observed, in the majority of WPCs, with a decrease in the Expected Value, highlighting the hedging characteristic of this instrument.

In Table 6, we present the aggregated traded volumes (avgMW), equilibrium price premium ($/MWh), and the welfare gain with respect to the base case (only forward and spot markets) when considering the proposed WInd-Op and the benchmark derivative, i.e., the standard put-and-call derivatives. Similarly to Case Study I, in comparison to the benchmark, we highlight the following points from the results of Table 6: the equilibrium obtained with the new derivative exhibits 1) a significantly higher total traded volume (2.9 times greater than the benchmark), 2) a lower premium price (54.7% lower than the benchmark), and 3) a greater overall welfare gain (2.7 greater than the benchmark).

To further illustrate the impact of the instruments in the key performance metrics (Expected Value, CVaR, and Overall Welfare Gain), the results in Table 6 are disaggregated per group, namely, WPCs

Table 5: Equilibrium results and relative performance metrics with respect to not trading the hedging instrument

Power Plant	$\boldsymbol{\lambda}^*$	$\boldsymbol{q}^*$	$\lvert\boldsymbol{q}^*\rvert$/**FEC**	$\Delta\ \mathbb{E}$	Δ CVaR	$\Delta\rho$	$\Delta\rho(\%)$
Brotas de Macaúbas	66.00	34.00	96%	−218,858	87,805	72,472	132%
Calango 1	66.00	26.00	93%	−164,291	51,070	40,302	127%
Calango 2	66.00	20.00	50%	−126,483	36,880	28,712	11%
Chapada I	66.00	94.00	85%	−597,546	290,921	246,498	50%
Curva dos Ventos	66.00	27.00	99%	−173,941	67,299	55,237	69%
Caetés II	66.00	−95.00	100%	602,857	386,571	397,385	51%
Pelourinho	66.00	17.00	72%	−108,790	42,365	34,807	30%
Serra de Santana 1 e 2	66.00	23.00	48%	−143,264	38,070	29,003	8%
Serra de Santana 3	66.00	− 7.00	13%	41,987	−134	1,972	0%
Cristal	66.00	31.00	64%	−194,285	119,594	103,900	23%
Caetité 123	66.00	28.00	72%	−178,316	44,331	33,198	281%
Brisa Potiguar I	66.00	56.00	62%	−354,225	58,780	38,129	13%
Pedra Cheirosa	66.00	0.00	0%	–	–	–	0%
Trairí	66.00	−35.00	36%	220,669	37,976	47,111	120%
Icaraizinho	66.00	− 4.00	19%	25,216	4,311	5,356	104%
Lapa	66.00	−17.00	100%	110,768	−55,642	60,845	13%
São Pedro	66.00	−16.00	100%	101,856	−55,236	23,310	6%
Juazeiro Solar	66.00	−14.00	40%	89,295	11,184	34,617	4%
Bom Jesus	66.00	−17.00	100%	106,948	−60,619	56,678	11%
Horizonte	66.00	−25.00	100%	155,966	−77,888	39,039	10%
Ituverava	66.00	−26.00	45%	167,329	−10,294	42,993	5%
Calcário	66.00	−35.00	100%	221,536	−119,429	119,246	12%
Nova Olinda	66.00	−23.00	37%	146,303	−137,536	4,383	1%
Assú V	66.00	− 1.00	11%	6,360	274	2,100	1%
Floresta	66.00	−25.00	100%	159,786	−93,651	83,755	13%
Sol do Futuro	66.00	−16.00	100%	103,129	−10,276	46,426	9%

Table 6: Aggregated Equilibrium results and relative performance metrics with respect to not trading the hedging instrument.

		Total Traded (avgMW)	**Eq. Premium (\$/MWh)**	**Total** $\boldsymbol{\Delta}\mathbb{E}$ **(\$)**	**Total** $\boldsymbol{\Delta}$CVaR **(\$)**	**Total** $\boldsymbol{\Delta\rho}$ **(\$)**
WInd-OP buyers/sellers	WPCs Buying	355	66	−2,260,005	837,115	682,259
	WPCs Selling	−140	66	890,730	428,724	451,824
	SPCs Selling	−215	66	1,369,276	−609,112	513,393
WInd-OP aggregated	(summary)	355	66	146	657,727	1,647,476
Put-and-Call buyers/sellers	WPC Buying	111	146	−735,777	316,517	263,903
	WPCs Selling	−37	146	243,599	77,983	86,264
	SPCs Selling	−74	146	492,179	−78,266	251,316
Put-and-Call aggregated	(summary)	111	146	0	316,234	601,482

and SPCs, and buyers and sellers. Note that the sum of the ΔCVaR metrics of the WPCs significantly increases for both buyers and sellers when considering the proposed derivative in comparison to the case where the benchmark derivative is considered. From the perspective of the SPCs, on the other hand, although we have a decrease in the total ΔCVaR, an overall higher increase in the Certainty Equivalent value is observed when considering the proposed derivative.

To showcase this effect by renewable agent, Figure 5 presents the relative change in Expected Value and Risk (valued by the difference between the Expected Value and the CVaR) for each renewable agent considered in this case study when trading the proposed WInd-Op. Similarly, Figure 6 depicts the same context but for the benchmark derivative. The square marker indicates the risk and return metrics when considering only the PPA and spot, while the round marker indicates the same metrics, adding the effect of the hedging instrument. The arrow connects the square marker and the round marker for each generator. With respect to Figure 5, by the direction of the arrows, it is possible to identify that most of the renewable agents gave up part of the Expected Value in favor of a risk reduction. Nevertheless, it is also observed that some agents (most of them playing the role of sellers) are willing to slightly increase the risk to obtain higher Expected Values. When comparing the results in Figure 5 with the ones in Figure 6, we can observe the higher benefits of the proposed instrument compared to the benchmark in terms of risk reduction or expected value gain.

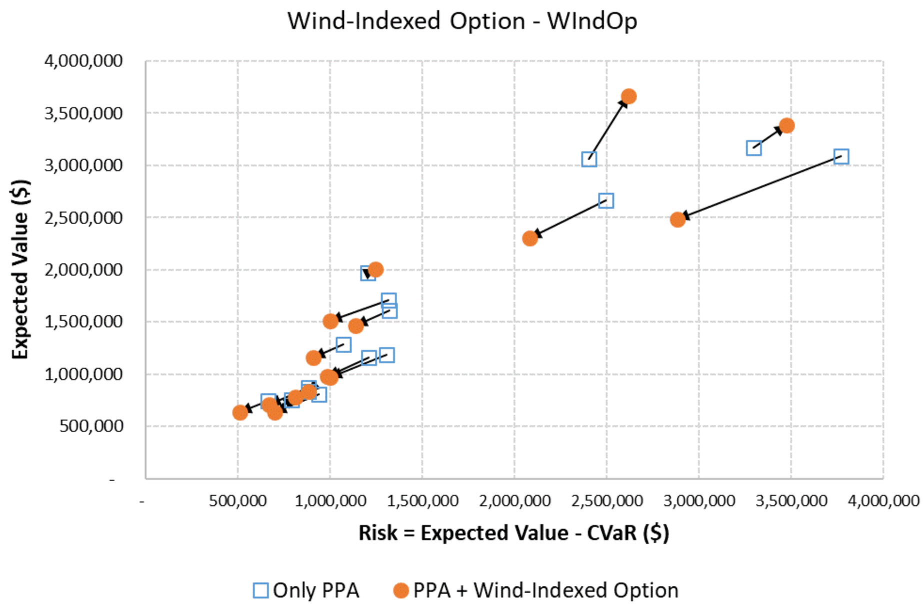

Figure 5: Relative change in risk and return (expected value) for each renewable agent in the equilibrium considering the proposed derivative.

Finally, we conduct a sensitivity analysis of the total welfare with respect to the forward involvement, i.e., with respect to a $\gamma 100\%$ of the total FEC amount, when considering the proposed derivative. Structurally, we parameterize the contracted PPA volume of each renewable agent as: $V_i = \gamma \text{FEC}_i, \ \forall \ i \in \mathcal{I}$, and vary $\gamma \in \{0.0, 0.1, \dots, 1.0\}$. Thus, $\gamma = 0.0$ represents a market with no long-term contracts, only spot, and, on the one hand, $\gamma = 1.0$ indicates that all renewable agents sell their maximum regulatory limit in PPAs. Table 7 showcases the resulting equilibrium price λ^* (Column 2), the total amount of the proposed derivative negotiated at the equilibrium (Column 3), the sum of the FEC of all WPCs that purchases the instrument (Column 4), the total traded volume of the proposed derivative at the equilibrium in percentage of the buyers' total FEC (Column 5), and

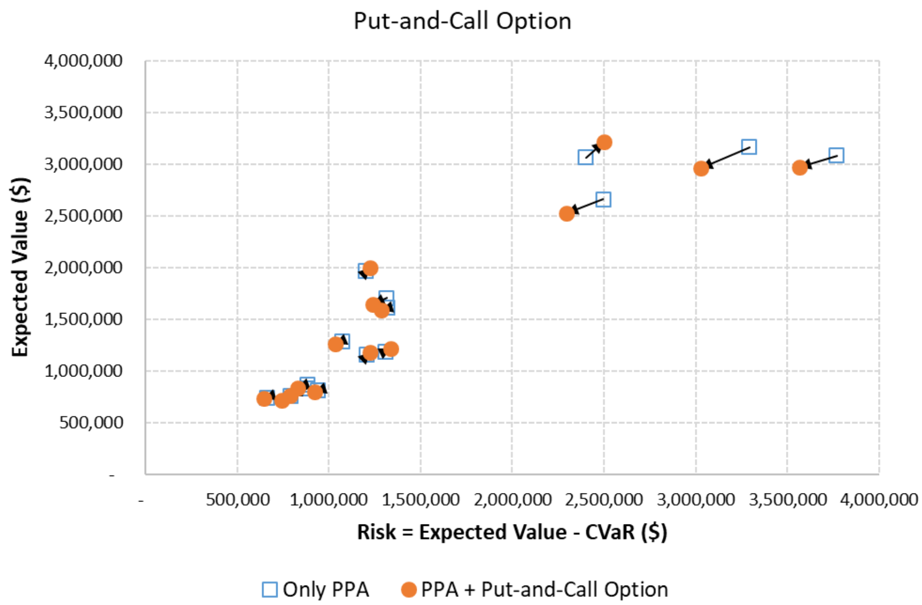

Figure 6: Relative change in risk and return (expected value) for each renewable agent in the equilibrium considering the benchmark (put-and-call) derivative.

the welfare gain (Column 6) with respect to the base case, not trading the WInd-Op for each value of $\gamma \in \{0.0, 0.1, \ldots, 1.0\}$. It is relevant to mention that all previously reported results in this second case study (Tables 4 and 5) correspond to $\gamma = 0.9$, penultimate line of Table 7.

Note in Table 7 that the higher the long-term contracting level, the more the proposed derivative is negotiated at the equilibrium. As a consequence, the equilibrium price (premium) and the total welfare gain increase as the forward involvement increases. Interestingly, a consequence of the welfare gain increase with the forward involvement, for a given absolute value of overall welfare, the total forward involvement can be higher in the presence of the proposed derivative. To quantify this relationship, Figure 7 presents the absolute value for the overall welfare (horizontal axis) and the forward involvement (in % of FEC) for each equilibrium. In this figure, the orange line depicts the equilibrium data when considering the proposed derivative, and the blue line depicts the welfare when not considering the derivative. So, the welfare gains reported in Table 7 are obtained through the horizontal difference between these two curves. Note, however, that if we analyze the vertical difference between these two curves, we can see that for the same overall welfare level, it is possible to sustainably increase the forward involvement in at least 8% of the renewable agent's FEC.

6. Conclusion

In this work, a new financial hedging instrument to mitigate the double-sided price-and-quantity risk faced by Wind Power Companies (WPCs) committed to long-term forward contracts is proposed. The proposed instrument, named Wind-Indexed Option (WInd-Op), is based on a Wind Power Performance Index (WPP-I), which adjusts the payoff of the proposed WInd-Op to the proportion of

Table 7: Equilibrium results for each value of $\gamma \in \{0.0, 0.1, \ldots, 1.0\}$.

γ	λ^*	Total Traded Volume	Sum FEC (Buyers)	Total Traded Volume (% Sum FEC)	Total $\Delta\rho$
0.0	11.00	105.00	379.00	28%	106,990
0.1	11.00	75.00	362.00	21%	132,352
0.2	13.00	95.00	352.00	27%	235,712
0.3	28.00	125.00	539.00	23%	294,163
0.4	34.00	166.00	562.00	29%	398,998
0.5	36.00	178.00	539.00	33%	611,325
0.6	44.00	227.00	594.00	38%	912,592
0.7	53.00	284.00	634.00	45%	1,149,080
0.8	55.00	287.00	536.00	54%	1,394,351
0.9	66.00	355.00	488.00	73%	1,647,476
1.0	71.00	362.00	568.00	64%	1,786,477

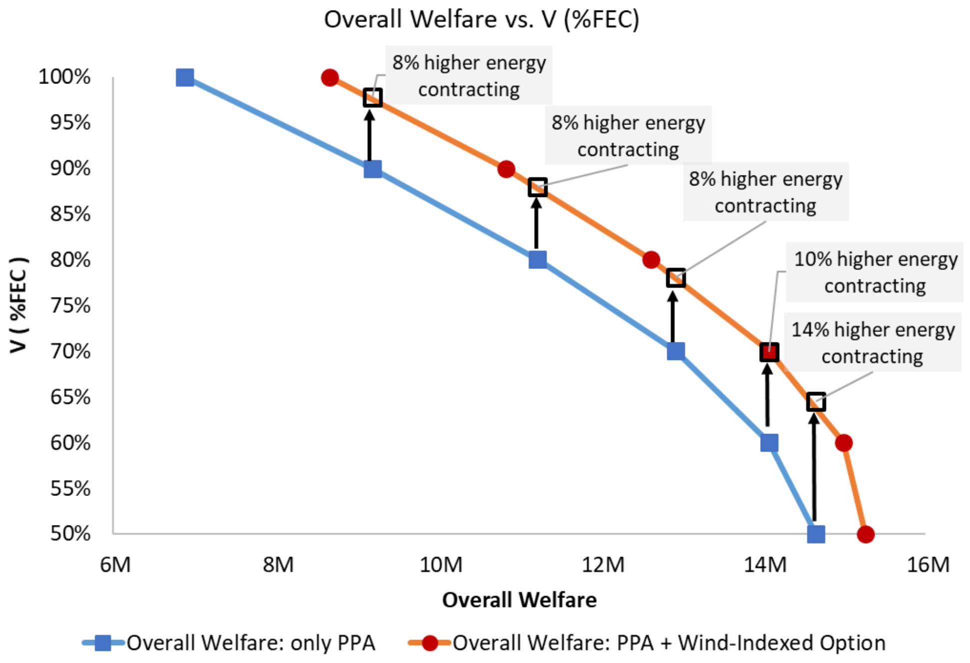

Figure 7: PPA volume vs total Certainty Equivalent value when considering (orange curve) and not considering (blue curve) the proposed derivative.

generation deficits and surpluses that is representative of a set of wind power generators. This allows the derivative to reduce unnecessary payments to mitigate the price and quantity risk of these generators.

Two numerical experiments based on the maximum welfare equilibrium approach were conducted to test the effectiveness and attractiveness of the proposed hedging instrument using real data from the Brazilian power system. Within the limitations of our case study hypotheses, data, and metrics, the empirical results obtained in this work enable us to convey the following conclusions and observations:

1. The proposed WInd-Op is effective in reducing the price-and-quantity risk of contracted WPCs (see last columns of Tables 5, 6, and 7), and the benefits increase with the holder's involvement

in the forward market (see last column of Table 7). This is observed when comparing the performance metrics to the base case, where only the forward and spot markets are considered.

2. The proposed Wind-Op enables WPCs to increase their forward involvement sustainably (see Figure 7). This fact has the potential to unlock additional long-term PPA contract volumes, benefiting consumers or utilities without compromising overall market welfare levels. This is consistent with the finance and risk literature [18] (as the presence of the derivative improves the market hedging options) and with the expected role for the proposed hedging instrument, which by alleviating the PQ-Risk, mainly increased by over-contracted positions, allows WPCs to increase their forward involvement while keeping the welfare level unchanged.
3. The proposed WInd-Op is more efficient in reducing the price and quantity risk and increasing the total welfare in comparison to the benchmark, the call-and-put derivative (See Table 6). Regarding this benchmark, results indicate that the equilibrium obtained with the proposed derivative exhibits a significantly higher total traded volume (is 2.9 times more liquid), lower premium prices (is 54.7% cheaper), and greater overall welfare benefit (2.7 times high the hedging benefit). These relevant benefits are aligned with the theoretical virtues of the proposed derivative in comparison to a call-and-put benchmark, namely, the ability to size the payment to the size of the risk exposure (based on the WPP-I) and its ability to avoid unnecessary payments in states that should not reduce losses.

7. Future Research

As future research avenues, we highlight the following interesting topics:

1. For the sake of conciseness and due to the limited scope of this paper, the indexology (the study, creation, maintenance, and analysis of financial indices) of the proposed Wind Power Performance Index was not discussed. It relies on relevant statistical and tailored methodologies needed to ensure important properties such as representativeness, relevance, consistency, transparency, reliability, reproducibility, etc. So, a more in-depth study of the processes and methods to generate a Wind Power Performance Index featuring all these properties is a relevant future research topic and constitutes an important step towards the practical implementation of the ideas proposed in this paper.
2. Although the ideas proposed in this work can be understood as applicable to other renewable sources, this extension requires extensive data collection and further analysis to define the scope, range, candidates for sellers, market needs and opportunities, and the correct timing and horizon. For instance, while solar power companies in the northeastern region of Brazil may be interested in the same time horizon and scale used in this work, hydros could be more interested in a monthly-based product with a duration of a few months to a whole year. In this case, wind

generators with complementary monthly generation patterns could be the relevant candidates for sellers. Note that even the wind power companies studied in this work could also benefit from other product designs, such as a monthly derivative, which can coexist in a more sophisticated renewable hedging market with different products. Therefore, the study of new products tailored to other sources, risks, and time scales constitutes a relevant extension and promising future research topic.

3. The consideration of more complex portfolio structures, e.g., considering storage (batteries or hydros), to back the proposed derivative also constitutes a relevant and interesting future research avenue.

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