Pontifícia Universidade Católica
do Rio de Janeiro

Gustavo Pires de Carvalho

Managing Renewable Energy Risk in the Brazilian Forward Market: The Impact of Hourly Hedging

Dissertação de Mestrado

Dissertation presented to the Programa de Pós–graduação em Engenharia Elétrica do Departamento de Engenharia Elétrica of PUC-Rio in partial fulfillment of the requirements for the degree of Mestre em Engenharia Elétrica.

Advisor : Prof. Alexandre Street de Aguiar
Co-advisor: Prof. Bruno Fanzeres dos Santos

Rio de Janeiro
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Prof. Alexandre Street de Aguiar
Advisor
Departamento de Engenharia Elétrica – PUC-Rio

Dr. Luiz Augusto Barroso
PSR – Energy Consulting and Analytics

Dr. João Carlos de Oliveira Mello
Thymos Energia

Rio de Janeiro, August 12th, 2025

Gustavo Pires de Carvalho

Gustavo Carvalho is currently responsible for the energy commercialization strategy and planning at Eletrobras. He holds a B.Sc. in Electrical Engineering with an extension in Risk Analysis from PUC-Rio, and an Executive MBA in Finance from FGV São Paulo. With over ten years of experience in the Brazilian power sector, he has worked in business strategy, regulatory affairs for distribution and generation, spot price (PLD) modeling for short, medium, and long-term horizons, portfolio management, and energy consulting. His professional interests include new business models and energy strategy, risk analysis, market design, regulatory frameworks, structured operations, portfolio optimization, and energy price formation mechanisms.

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To my beloved son Arthur, whom I wish may cultivate a love for learning and a continuous pursuit of knowledge.

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Abstract

Carvalho, Gustavo Pires de; Aguiar, Alexandre Street de (Advisor); Santos, Bruno Fanzeres dos (Co-Advisor). **Managing Renewable Energy Risk in the Brazilian Forward Market: The Impact of Hourly Hedging**. Rio de Janeiro, 2025. 41p. Dissertação de Mestrado – Departamento de Engenharia Elétrica, Pontifícia Universidade Católica do Rio de Janeiro.

A shift towards a carbon-neutral generation matrix is underway worldwide. In Brazil, where long-term forward markets drive investments, this trend is not different. For instance, long-term contracted renewable generation investors face the so-called price-and-quantity risk, which materializes whenever a generator falls short of producing the contracted amount and has to purchase this deficit at high spot prices. Notwithstanding, some renewable sources exhibit relevant hourly complementary generation profiles, e.g., wind and solar in the Northeastern Region of Brazil, suggesting a synergy that can be explored through swap mechanisms to mitigate the priceand-quantity risk. Therefore, in this work, we investigate a decentralized approach based on hourly swaps, i.e., the exchange of forward contracts with different delivery hours. With these new hedging instruments, renewable agents can adjust their current flat forward positions and modulate them according to their generation profile and risk aversion level, thus minimizing the exposure to price-and-quantity risk through a pure financial market mechanism. We evaluate the benefits of the proposed mechanism through market equilibria using real data from the Brazilian power system. Results provide relevant evidence that the proposed hedging instrument should be beneficial to market agents and even foster higher long-term forward involvements with lower risk levels.

Keywords

Electricity Market; Forward Contract; Market Design; Equilibrium; Risk Management.

Resumo

Carvalho, Gustavo Pires de; Aguiar, Alexandre Street de; Santos, Bruno Fanzeres dos. **Gerenciamento do Risco de Energia Renovável no Mercado a Termo Brasileiro: O Impacto do Hedge Horário**. Rio de Janeiro, 2025. 41p. Dissertação de Mestrado – Departamento de Engenharia Elétrica, Pontifícia Universidade Católica do Rio de Janeiro.

A mudança para uma matriz de geração neutra em carbono está em curso em todo o mundo. No Brasil, onde os mercados a termo de longo prazo impulsionam os investimentos, essa tendência não é diferente. Por exemplo, os investidores em geração renovável contratada a longo prazo enfrentam o chamado risco de preço e quantidade, que se materializa sempre que um gerador não consegue produzir a quantidade contratada e deve comprar esse déficit a preços *spot* elevados. Não obstante, algumas fontes renováveis exibem perfis de geração horária complementares relevantes, por exemplo, eólica e solar na Região Nordeste do Brasil, sugerindo uma sinergia que pode ser explorada através de mecanismos de *swap* para mitigar o risco de preço e quantidade. Portanto, neste trabalho, investigamos uma abordagem descentralizada baseada em *swaps* horários, ou seja, a troca de contratos a termo com diferentes horários de entrega. Com estes novos instrumentos de *hedge*, os agentes renováveis podem ajustar as suas atuais posições a termo *flats* e modulá-las de acordo com o seu perfil de geração e nível de aversão ao risco, minimizando assim a exposição ao risco preço-quantidade através de um mecanismo de mercado puramente financeiro. Avaliamos os benefícios do mecanismo proposto através de equilíbrios de mercado utilizando dados reais do sistema elétrico brasileiro. Os resultados fornecem evidências relevantes de que o instrumento de *hedge* proposto deve ser benéfico para os agentes de mercado e até mesmo promover maiores contratações a longo prazo com níveis de risco mais baixos.

Palavras-chave

Mercado de Eletricidade; Contrato a termo; Desenho de Mercado; Equilíbrio; Gestão de Risco.

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I'm a greater believer in luck, and I find the harder I work the more I have of it.

Thomas Jefferson

1
Introduction

Over the past decades, most countries around the globe have committed to reducing greenhouse gas emissions through their economic sectors and supply chains, aiming at achieving a carbon-neutral economy in the near term. In the particular context of the electricity sector, this engagement is currently being unfolded through the replacement of conventional thermal generators by variable Renewable Energy Sources (vRES) (KÅBERGER, 2018).

A critical impact after this movement, however, is a substantial increase in energy supply variability due to the intrinsic weather-dependency nature of vRES production, adding a new layer of uncertainty in both system operation costs and energy spot prices (KYRITSIS; ANDERSSON; SERLETIS, 2017), and exposing the electricity sector agents to various risks.

In 2004, the Brazilian regulatory system was updated to use long-term forward contracts, or Power Purchase Agreements (PPA), as a key mechanism to reduce the dependence on weak short-term spot-price signals for expansion and ensure supply adequacy (PEREIRA; BARROSO; ROSENBLATT, 2004). At that date, Brazil already accounted for a significant share of zero-marginal cost generation (on average, more than 80% of the generation was hydro-based). Thus, the utilization of forward contracts was one of the main ingredients responsible for the secure development of renewables in this country.

However, despite the relevant changes in the generation matrix, with intermittent renewables (wind and solar) going from the least to the second position in annual generation, the market structures and main hedging instruments have not changed much since then. From an economic perspective, this desynchronization poses a critical risk to renewable agents when selling energy through standard (flat) forward contracts, the so-called price-and-quantity risk. This risk materializes whenever a generator has an excess of forward contracts compared to its actual generation and must clear this difference at high spot prices (OUM; OREN; DENG, 2006).

Interestingly, based on historical data from the Brazilian power system, the prevalence of hours with spot prices going against the wind power generation (high spot prices when wind generation is low or the contrary) in the main renewable generation region (northeast of Brazil) is non-negligible. This fact is depicted in Figure 1.1, where the correlation between wind generation and spot prices in the northeastern area of Brazil, calculated with the hourly data for each month of the historical records from Jan/2019 to Dec/2020, is mainly negative.

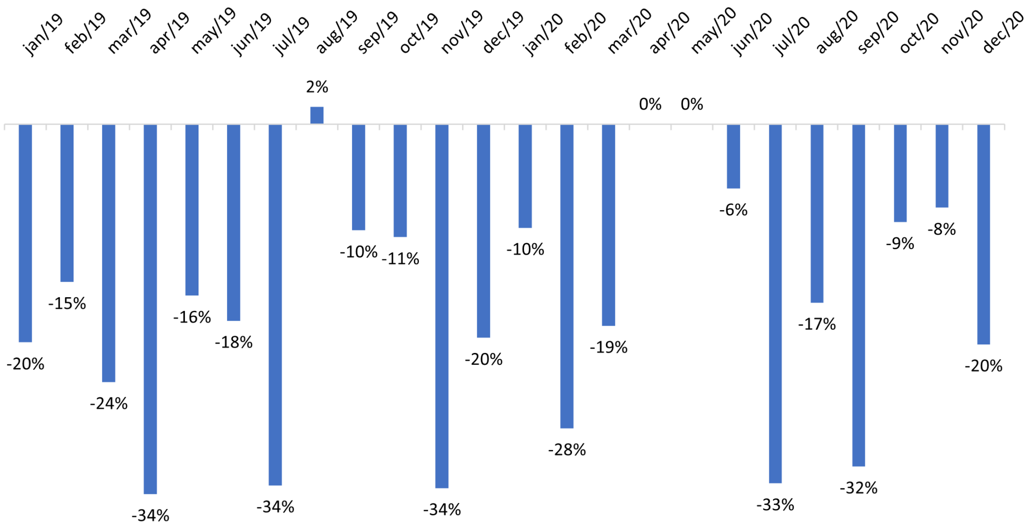

Figure 1.1: Monthly correlation coefficients (calculated with hourly data) for the wind generation and spot prices in the northeastern area of Brazil.

Nonetheless, the complementarity of wind and solar generators in the northeastern region of Brazil is paramount. Figure 1.2 presents the average hourly production of each renewable source (wind and solar) as a percentage of the total average production among all hours. It is clear that a more stable and, thereby, less risky profile can be achieved by combining these complementary hourly profiles. Therefore, this dissertation focuses on the potential hedging benefits complementary renewables can obtain in the Brazilian forward market.

Different approaches have been studied in technical literature over the past decades to tackle this challenge (we refer to (CONEJO; CARRIÓN; MORALES, 2010; WOLAK, 2021) for wide discussion). For instance, (MO; GJELSVIK; GRUNDT, 2001) integrates and optimizes the scheduling and contract portfolio position of a hydropower generator by proposing a risk-constrained optimization model with minimum revenue targets. In (CONEJO et al., 2008), a two-stage stochastic model is presented to assess the optimal involvement of a generator in future contracts for electricity to mitigate the risk of spot price uncertainty. Later, in (PINEDA; CONEJO, 2012), the optimal composition of a portfolio of derivatives is studied with the main objective of hedging the risk faced by an electricity producer due to selling prices uncertainty and availability of its production units. In (GARCIA et al., 2017), two risk-averse portfolio allocation models seeking to optimally clear the generator energy production in different trading environments, including spot

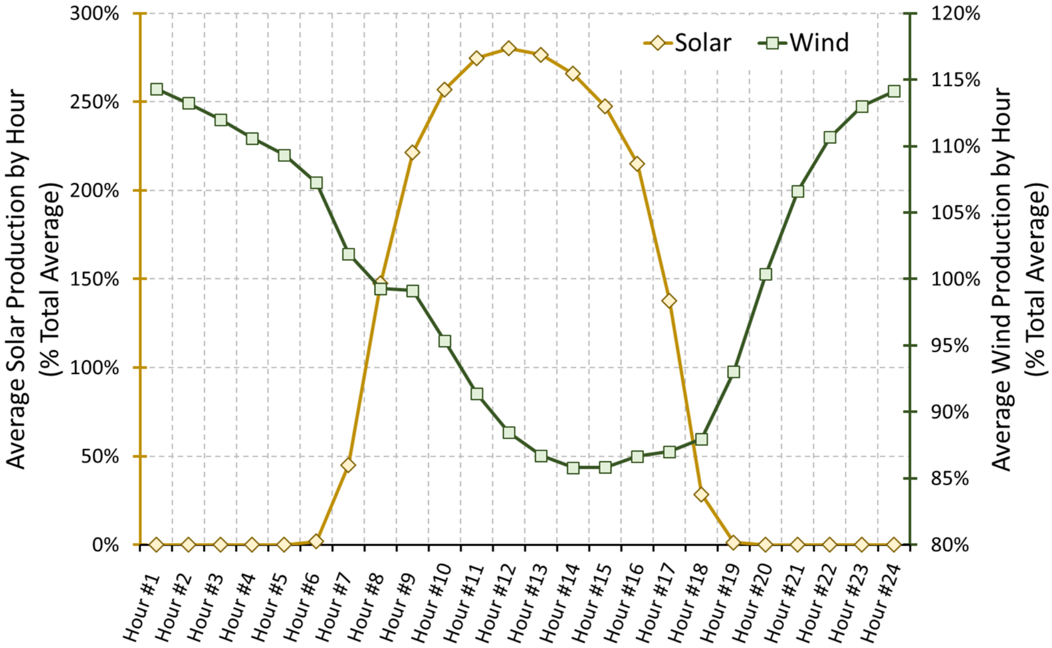

Figure 1.2: Average hourly wind and solar generation profiles in the northeastern area of Brazil as a percentage of the average.

and contract markets, were studied. A review of portfolio problems identifying the appropriate contracting levels to maximize the generator value and welfare can be found in (ODEH; WATTS; NEGRETE-PINCETIC, 2018).

Although optimizing contract amounts and derivatives in the portfolio helps mitigate the market risks faced by a generator, the uncertainty in the production of non-controllable renewables still challenges their economic sustainability. Therefore, based on the diversification principle, a follow-on approach explored in the literature is to define a portfolio with complementary vRES to mitigate the price-and-quantity risk. For instance, (STREET et al., 2009) proposes a joint risk-averse portfolio selection model to combine a biomass generation unit (using sugarcane waste) and a small run-of-riven hydro to back a forward contract position in the Brazilian electricity market. By acknowledging the difficulty in predicting spot prices, (FANZERES; STREET; BARROSO, 2014b) extend these ideas by proposing a two-stage hybrid robust-stochastic portfolio selection model to combine a small hydro and a wind power generator under an endogenous stress-test-based methodology. In (FANZERES; STREET; BARROSO, 2014a), the imprecision in the random variables' scenario outcomes is, for the first time in the literature, translated into a distributional robust approach, modeling a type of ambiguity aversion. Further on, in (MAIER; STREET; MCKINNON, 2016), a portfolio strategy was proposed based on the combination of investment opportunities in multiple complementary renewable generators with the possibility of selling contracts in the two main contracting environments in Brazil. More recently, (BRIGATTO; FANZERES, 2022) proposes a combined portfolio of renewables and call/put options to hedge the supply of forward contracts against ambiguity in spot price probability distribution. Finally, in (ARANHA et al., 2023), a multi-stage stochastic programming model was studied to characterize the sequential decision-making process of a dynamically adjusted portfolio of contracts taking into account long- and short-term uncertainty factors for a wind power producer.

In contrast to a pure combination of complementary sources, the investment in energy storage systems, such as hydro pumping or batteries, were studied in (GARCíA-GONZáLEZ et al., 2008) and (HADJIPASCHALIS; POULLIKKAS; EFTHIMIOU, 2009), respectively, to handle production variability and reduce the exposure to spot price uncertainty.

As an attempt to provide an alternative approach where individual parties do not need to be part of the same portfolio, (FREIRE et al., 2015) proposes the design of a pool of vRES with complementary production profiles based on cooperative game concepts. In this scheme, individual companies transfer part of their generation rights to the pool, which manages the optimal trading strategy of the total generation and assigns to each company a quota of the pool's financial earnings according to the nucleolus allocation method.

Nevertheless, despite the benefits of previously reported approaches in mitigating the price-and-quantity risks faced by contracted renewable agents, these approaches primarily rely on specifically structured risk-management portfolio strategies. These strategies either require a non-negligible amount of capital, such as for the acquisition of a generation portfolio, or rely on an energy trading company managing the risk of a renewable pool. Additionally, relevant information about the generation profiles must be shared among participants. Finally, these strategies are typically tailored to specific units and generation profiles, resulting in low liquidity. All these factors pose challenges to their practical implementation.

In this work, we study the benefits of an alternative approach, where agents interact through standardized forward contracts for specific hourly delivery. While some market fees may be charged depending on the market design in this context, this new paradigm enables 1) reduced administrative fees or investment capital, 2) information privacy, and 3) the possibility of more liquid structures.

1.1 Objective, contributions, and thesis outline

The objective of this work is to explore the economic benefits of complementary wind and solar generators in the Brazilian electricity forward market based on a pure market-oriented hedging mechanism. More specifically, we propose the study of a decentralized over-the-counter financial hedging market where renewable agents can freely trade mid-term forward contracts with delivery at specific hours of the day (i.e., hourly energy swaps). The goal of this market is to allow renewables to adjust their long-term contract positions (e.g., based on flat PPAs traded with consumers) according to their foreseen short-term generation dynamics, spot price uncertainty, and risk profile. Within this context, we test the hypothesis that a market-oriented reallocation mechanism based on week-ahead hourly energy swaps can improve the (risk-adjusted) overall welfare of renewable generators with different hourly generation profiles in Brazil.

To test this hypothesis, we develop a two-stage stochastic optimization model to estimate a competitive equilibrium for long-term-contracted wind and solar generators negotiating the proposed derivatives (hourly forward contracts). The model allows considering 1) 24 simultaneous products, each of which with delivery at a specific hour of the day, but spanning, e.g., a whole week, 2) heterogeneous risk-averse profiles based on the conditional value-at-risk (CVaR) coherent risk measure (ARTZNER et al., 1999); and 3) the long-term contracting position of each market player. The model determines the maximum (risk-adjusted) overall welfare based on the swap negotiations for the 24 different contracts. Based on the concepts of the proposed mechanism and real data from the Brazilian electricity market (renewable generation and spot prices), our main contribution is to bring relevant evidence that the proposed market mechanism is an effective way to improve the welfare of contracted wind and solar generators in Brazil.

The remainder of this dissertation is as follows. In Section 2 we start presenting the decision-making problem of a single renewable agent for selecting its best involvement in the proposed swap market. In Section 3, we develop the equilibrium model and its properties. Then, in Section 4, a wide numerical analysis with real data from the Brazilian system is performed to evaluate the potential benefits of the risk mitigation and welfare increase that the proposed market can provide. Finally, Section 5 devises the key conclusions and insights found in this work.

2
Single Agent Decision Problem

The main objective of this work is to propose and study the design of a decentralized market-based environment for investors in vRES to hedge against price-and-quantity risk by modulating their forward involvement through the hours of the day. Structurally, the proposed hedging market mechanism comprises standardized hourly forward contracts allowing wind and solar generators to swap energy for the following week, for instance, in an over-the-counter market environment (see (RIBEIRO et al., 2023) for a detailed benchmark of market formats). For expository purposes and without loss of generality, we assume that each renewable agent is involved in a long-term PPA with a consumer.

2.1
Contracts and Revenue Expression

Formally, let $\mathcal{I}$ be a n-dimensional set of renewable generators (agents) seeking to hedge against their spot-market exposure, where each agent $i \in \mathcal{I}$ is assumed to be contracted in a long-term PPA with known price $\left(P_i\right)$ and volume $\left(V_i\right)$. Furthermore, let $\mathcal{T} = \{1, \ldots, T\}$ to denote the set of hours that spans the week-ahead trading horizon (i.e., $T = 168$) and $h : \mathcal{T} \rightarrow \{1, \ldots, 24\}$ a function that maps the time period index $t \in \mathcal{T}$ onto a specific hour of the day. We assume a marketplace with 24 simultaneous but distinct products, each of which with delivery at only one specific hour of the day during the contract horizon (i.e., one week in this study). For instance, product 10 am is a one-week forward contract that is activated every day during the contract horizon only from 10:00 until 10:59 (whole minute included). Within this context, we define $\boldsymbol{\lambda} \triangleq \{\lambda_1, \ldots, \lambda_{24}\}$ as the vector containing the market prices for all 24 products. Thus, by acting in the proposed market with a quantity position in each available product given by $\boldsymbol{Q}_i \triangleq \{Q_{i,1}, \ldots, Q_{i,24}\}$, the net revenue stream of an agent $i \in \mathcal{I}$ within the week-ahead trading horizon follows expression (2-1) below:

$$R_i\left(\boldsymbol{\lambda}, \boldsymbol{Q}_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}\right) = \sum_{t \in \mathcal{T}} \left[P_i \, V_i + \left(\tilde{G}_{i,t} - V_i\right)\tilde{\pi}_t \; + \left(\lambda_{h(t)} - \tilde{\pi}_t\right) Q_{i,h(t)}\right] \tag{2-1}$$

In (2-1), $\tilde{\boldsymbol{G}}_i \triangleq \left\{\tilde{G}_{i,t}\right\}_{t \in \mathcal{T}}$ represents the stochastic generation of the renewable power plant owned by agent $i \in \mathcal{I}$ at hour $t \in \mathcal{T}$, and $\tilde{\boldsymbol{\pi}} \triangleq \left\{\tilde{\pi}_t\right\}_{t \in \mathcal{T}}$ stands for the stochastic energy spot price along $t \in \mathcal{T}$. Financially, the first two terms in (2-1) recover the cash flow of the long-term PPA within the week-ahead trading horizon, whereas the third term reflects the revenue from each hourly forward contract sold (if $Q_{i,h(t)} > 0$) or bought (if $Q_{i,h(t)} < 0$) in the market.

Note that, expression (2-1) can be rewritten as follows:

$$R_i\Big(\boldsymbol{\lambda}, \boldsymbol{Q}_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}\Big) = \sum_{t \in \mathcal{T}} \left[\Big(P_i\, V_i + \lambda_{h(t)} Q_{i,h(t)}\Big) \;+ \Big(\tilde{G}_{i,t} - V_i - Q_{i,h(t)}\Big)\tilde{\pi}_t \right] \quad (2\text{-}2)$$

The net revenue stream expression (2-2) explicitly highlights the adjusted price-and-quantity risk, given by the long-term PPA position V_i adjusted by the hourly contracts $Q_{i,h(\cdot)}$. More specifically, assuming that $Q_{i,h(\cdot)} = 0$, on the one hand, if a high volume is sold in the long-term contract, i.e., V_i is high, according to the first term of expression (2-1), the fixed revenue increases. On the other hand, according to the second term of expression (2-1), in this case, the likelihood of a negative clearing in the spot market also increases. Furthermore, although lowering the long-term PPA quantity helps mitigate this risk, it also reduces the fixed revenue amount received by the contract in hours with high generation. Therefore, the hourly contract gives renewable generators flexibility to increase the total contracted amount in the hours in which the generation is typically high and reduce it in the hours in which the generation is expected to be low. In this context, the price for these adjustments will follow the market availability of each source and their risk profile.

Figure 2.1 illustrates two consecutive days within the contract horizon. The renewable generation of a given power plant is shown in dotted green. It is contrasted with the total forward volume adjusted hourly (black horizontal line) based on the quantities sold (upward arrows) and purchased (downward arrows) that add to or subtract from the long-term PPA volume (black horizontal dashed line).

2.2 The Risk-Averse Portfolio Optimization Problem

To characterize the risk-adjusted willingness-to-contract for each agent $i \in \mathcal{I}$, we use a risk-averse portfolio optimization problem that finds the best portfolio (quantities) of hourly contracts, $\boldsymbol{Q}_i^*\big(\boldsymbol{\lambda}\big) \triangleq \Big\{Q_{i,1}^*\big(\boldsymbol{\lambda}\big), \ldots, Q_{i,24}^*\big(\boldsymbol{\lambda}\big)\Big\}$, as a function of their market prices $\boldsymbol{\lambda}$. The willingness-to-contract function, also known as best response function, is the basis for the market equilibrium model that will be developed in the next section.

Formally, let ρ_{θ_i} to denote a θ_i-parameterized certainty equivalent that characterizes the risk attitude of player $i \in \mathcal{I}$. Based on (STREET, 2010), in this work, we consider a certainty equivalent based on a convex combination

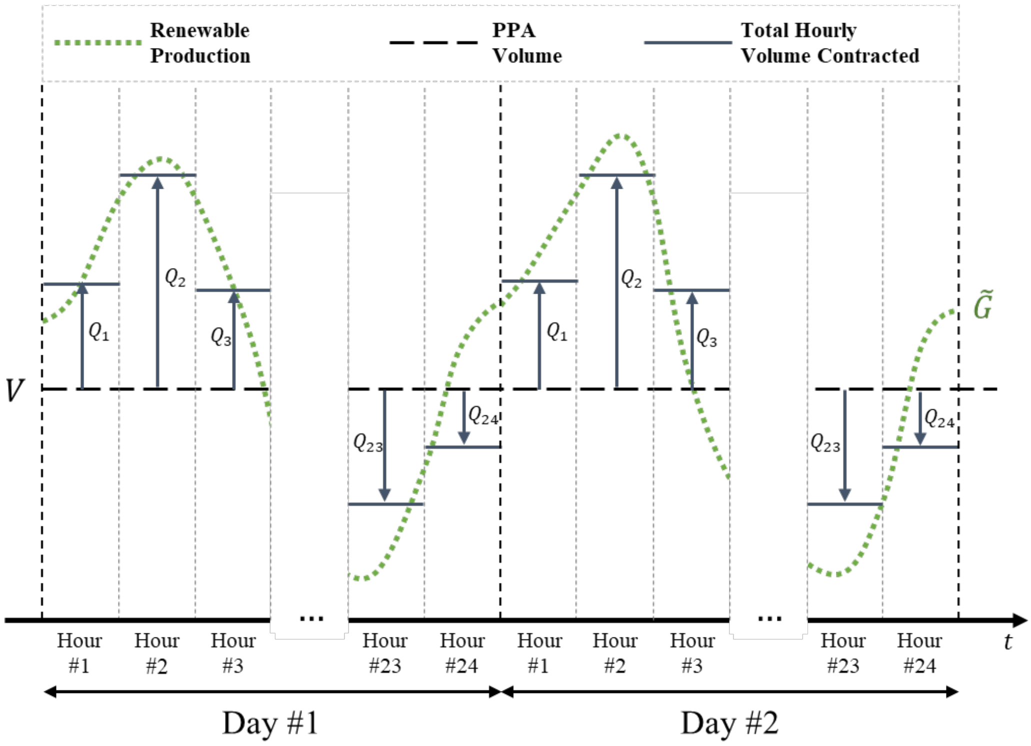

Figure 2.1: Long-term contract adjustment for different hours of two consecutive days within the contract horizon.

between the *Expected Value* of the net revenue stream and the left-tail α-*Conditional Value-at-Risk* (CVaR_α) as follows:

$$\rho_{\theta_i}\Big(R_i\Big) = \beta_i \, \text{CVaR}_{\alpha_i}\Big(R_i\Big) + \Big(1 - \beta_i\Big) \, \mathbb{E}\Big(R_i\Big) \tag{2-3}$$

In (2-3), $\theta_i \triangleq \{\alpha_i, \beta_i\}$ with $\beta_i \in [0, 1]$ and $\alpha_i \in (0, 1]$. Both α_i and β_i play the role of risk-averse parameters for the renewable agent $i \in \mathcal{I}$. While α_i stands for the confidence level of the CVaR measure, indicating the $(1 - \alpha_i)$-quantile up to which the worst net revenues scenarios are averaged, (β_i) balances the weight given to the CVaR measure and the Expected Value. We refer to Figure 2.2 for the CVaR and expected value components of the certainty equivalent for an illustrative revenue probability density function. Therefore, an economic risk-averse agent $i \in \mathcal{I}$ should act in the hedging market aiming to maximize this metric.

It is relevant to mention that the risk measure in (2-3) is general enough to map a variety of risk profiles. For instance, if the renewable agent is risk neutral, then it can be characterized by setting $\beta_i = 0$, meanwhile increasing the value of β_i towards 1 induces stronger levels of risk aversion.

Finally, for a given 24-dimensional vector of prices $\boldsymbol{\lambda}$, the 24-dimensional vector of quantities defining the optimal willingness-to-contract of an agent

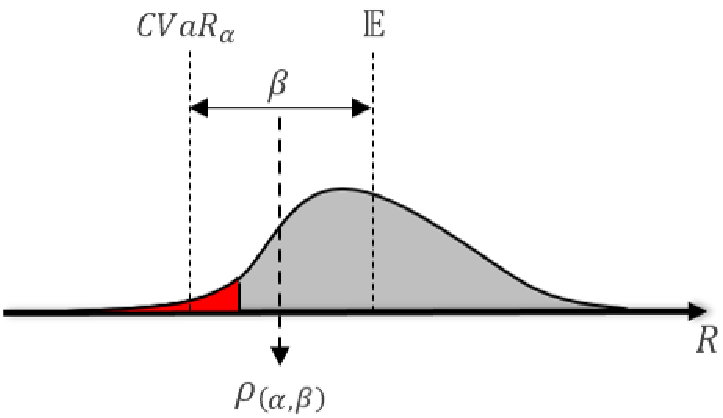

Figure 2.2: Expected value, CVaR, and the certainty equivalent for a probability density function of an illustrative random variable $\tilde{R}$.

$i \in \mathcal{I}$ for each hourly contract is given by

$$\boldsymbol{Q}_i^*\Big(\boldsymbol{\lambda}\Big) \in \underset{\mathbf{Q}_i \in \mathcal{Q}_i}{\arg\max} \left\{ \rho_{\theta_i}\Bigg(R_i\Big(\boldsymbol{\lambda}, \boldsymbol{Q}_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}\Big)\Bigg) \right\} \tag{2-4}$$

In (2-4), $\mathcal{Q}_i$ represents a convex region that can represent the feasible contracting decisions for a given agent $i \in \mathcal{I}$ comprising the 24 products (it is typically comprised of a box constraint, but it can also consider, e.g., budget constraints involving all products if needed).

3
Market Model and Properties

The Brazilian regulatory framework still follows a centralized-base dispatch model. In this framework, renewable generation is centrally forecasted by the system operator and subtracted from the load forecast considered in the day-ahead unit commitment model from where spot prices are derived. So, spot prices in Brazil are defined daily based on a deterministic day-ahead unit commitment scheduling model, and all forward contracts are cleared against these prices within an over-the-counter scheme.

Thus, to evaluate the newly proposed products, we rely on the same paradigm. In this sense, we assume a decentralized financial over-the-counter forward market where offers can be placed in an online platform and negotiated with transparency (counterparts can see all buy and sell orders and bids for each one of them) and low transaction costs.

To study the main properties and effectiveness of the proposed hedging products, we use economic equilibrium tools (GABRIEL et al., 2013). As customary in the technical literature, we use the competitive equilibrium, calculated through the maximum welfare approach, to study the potential benefits of this market (see (O'NEILL et al., 2005) and (YANG; FUJISHIGE, 2017)).

Roughly speaking, economic equilibrium is a particular state of the economy in which both willingness-to-supply and willingness-to-consume for the goods in the analysis are balanced among all participants. In the context of this work, the referred state of the economy is condensed into the contract prices $\boldsymbol{\lambda}$ and an economic equilibrium is reached whenever a given collection of prices ensures that the total optimal willingness-to-sell is equal to the total optimal willingness-to-buy, i.e., given a vector of prices $\boldsymbol{\lambda}$,

$$\sum_{i \in \mathcal{I}} Q^*_{i,j}\Big(\boldsymbol{\lambda}\Big) = 0, \qquad \forall\, j \in \{1, \ldots, 24\} \tag{3-1}$$

In Theorem 1, we formalize the mathematical-programming-based formulation used to identify an economic equilibrium state for the proposed hedging market. It considers the generators' risk profiles and computes the equilibrium prices based on strong duality theory.

Theorem 1 *Let ρ_{θ_i} to denote the utility of a given player $i \in \mathcal{I}$, characterized by a θ_i-parameterized coherent risk measure (e.g., see (STREET, 2010)), and*

Λ the set of equilibrium prices defined as

$$\Lambda = \left\{ \boldsymbol{\lambda} \triangleq \left\{\lambda_j\right\}_{j=1}^{24} \in \mathbb{R}^{24} \;\middle|\; \exists \left\{\boldsymbol{Q}_i^*\right\}_{i\in\mathcal{I}} \in \mathbb{R}^{|\mathcal{I}|} \times \mathbb{R}^{24} : \right.$$
$$\boldsymbol{Q}_i^* \in \arg\max_{\mathbf{Q}_i \in \mathcal{Q}_i} \left\{ \rho_{\theta_i}\Big(R_i\Big(\boldsymbol{\lambda}, \boldsymbol{Q}_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}\Big)\Big)\right\}, \qquad \forall\, i \in \mathcal{I};$$
$$\left. \sum_{i\in\mathcal{I}} Q_{i,j}^* = 0, \qquad \forall\, j \in \{1,\ldots,24\} \right\} \tag{3-2}$$

with $R_i(\cdot)$ denoting the net revenue stream of agent $i \in \mathcal{I}$ defined in (2-2)*. Furthermore, consider the following convex optimization problem:*

$$\max_{\{\mathbf{Q}_i\}_{i\in\mathcal{I}}} \sum_{i\in\mathcal{I}} \sum_{t\in\mathcal{T}} \left[P_i\, V_i + \rho_{\theta_i}\Big(\Big(\tilde{G}_{i,t} - V_i - Q_{i,h(t)} \Big) \tilde{\pi}_t \Big) \right] \tag{3-3}$$

subject to:

$$\sum_{i\in\mathcal{I}} Q_{i,j} = 0, \qquad : \mu_j \qquad \forall\, j \in \{1,\ldots,24\} \tag{3-4}$$

$$\mathbf{Q}_i \in \mathcal{Q}_i, \qquad \forall\, i \in \mathcal{I} \tag{3-5}$$

with $\boldsymbol{\mu} \triangleq \left\{\mu_j\right\}_{j=1}^{24}$ being the dual variable of the balance constraint (3-4)*. If*

$$\boldsymbol{\lambda}^* = \left\{ \mu_j^* \frac{24}{|\mathcal{T}|} \right\}_{j=1}^{24} \tag{3-6}$$

with $\boldsymbol{\mu}^*$ a solution point in the dual space of (3-3)–(3-5)*, then $\boldsymbol{\lambda}^* \in \Lambda$.*

Proof. Firstly, let $\mathcal{L} : \times_{i\in\mathcal{I}} \mathcal{Q}_i \times \mathbb{R}^{24} \to \mathbb{R}$ be a Lagrangian function associated with problem (3-3)–(3-5), defined as follows:

$$\begin{aligned}
\mathcal{L}\Big(\mathbf{Q}_i, \ldots, \mathbf{Q}_{|\mathcal{I}|}, \boldsymbol{\mu}\Big) &= \sum_{i\in\mathcal{I}} \sum_{t\in\mathcal{T}} \left[P_i\, V_i + \rho_{\theta_i}\Big(\Big(\tilde{G}_{i,t} - V_i - Q_{i,h(t)} \Big) \tilde{\pi}_t \Big) \right] + \sum_{j=1}^{24} \mu_j \sum_{i\in\mathcal{I}} Q_{i,j} \\
&= \sum_{i\in\mathcal{I}} \sum_{t\in\mathcal{T}} \left[P_i\, V_i + \rho_{\theta_i}\Big(\Big(\tilde{G}_{i,t} - V_i - Q_{i,h(t)} \Big) \tilde{\pi}_t \Big) + \mu_{h(t)} \frac{24}{|\mathcal{T}|} Q_{i,h(t)} \right] \\
&= \sum_{i\in\mathcal{I}} \rho_{\theta_i}\Big(R_i\Big(\boldsymbol{\mu}\frac{24}{|\mathcal{T}|}, \boldsymbol{Q}_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}} \Big)\Big)
\end{aligned} \tag{3-7}$$

where the last step holds because ρ_{θ_i} is a coherent risk measure for each agent $i \in \mathcal{I}$, thus satisfying the *translation invariance*[1] property (see (STREET,

[1]The translation invariance property used in this work means: If R is a random revenue

2010)). The Lagrangian Dual optimization problem of (3-3)–(3-5) can be written as

$$\min_{\boldsymbol{\mu}} \left\{ \max_{\{\mathbf{Q}_i \in \mathcal{Q}_i\}_{i\in\mathcal{I}}} \left\{ \mathcal{L}\Big(\mathbf{Q}_i, \ldots, \mathbf{Q}_{|\mathcal{I}|}, \boldsymbol{\mu}\Big) \right\} \right\} \tag{3-8}$$

which is equivalent to

$$\min_{\boldsymbol{\mu}} \sum_{i\in\mathcal{I}} \left[\max_{\mathbf{Q}_i \in \mathcal{Q}_i} \left\{ \rho_{\theta_i}\left(R_i\Big(\boldsymbol{\mu}\frac{24}{|\mathcal{T}|}, \boldsymbol{Q}_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}\Big)\right) \right\} \right] \tag{3-9}$$

due to the separability of the Lagrangian function (3-7) among agents. Furthermore, we can also write (3-9) as follows:

$$\min_{\boldsymbol{\mu}, \boldsymbol{Q}_i^*} \sum_{i\in\mathcal{I}} \rho_{\theta_i}\left(R_i\Big(\boldsymbol{\mu}\frac{24}{|\mathcal{T}|}, \boldsymbol{Q}_i^*, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}\Big)\right) \tag{3-10}$$

subject to:

$$\boldsymbol{Q}_i^* \in \arg\max_{\mathbf{Q}_i \in \mathcal{Q}_i} \left\{ \rho_{\theta_i}\left(R_i\Big(\boldsymbol{\mu}\frac{24}{|\mathcal{T}|}, \boldsymbol{Q}_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}\Big)\right) \right\}, \quad \forall\, i \in \mathcal{I} \tag{3-11}$$

Since ρ_{θ_i} is concave, problem (3-3)–(3-5) is a convex optimization problem and strong duality holds (BOYD; VANDENBERGHE, 2004). Therefore, the economic equilibrium condition (3-1) is a valid equation in (3-10)–(3-11). Thus, we have that

$$\min_{\boldsymbol{\mu}, \boldsymbol{Q}_i^*} \sum_{i\in\mathcal{I}} \rho_{\theta_i}\left(R_i\Big(\boldsymbol{\mu}\frac{24}{|\mathcal{T}|}, \boldsymbol{Q}_i^*, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}\Big)\right) \tag{3-12}$$

subject to:

$$\boldsymbol{Q}_i^* \in \arg\max_{\mathbf{Q}_i \in \mathcal{Q}_i} \left\{ \rho_{\theta_i}\left(R_i\Big(\boldsymbol{\mu}\frac{24}{|\mathcal{T}|}, \boldsymbol{Q}_i, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}}\Big)\right) \right\}, \quad \forall\, i \in \mathcal{I} \tag{3-13}$$

$$\sum_{i\in\mathcal{I}} Q_{i,j}^* = 0, \qquad \forall\, j \in \{1, \ldots, 24\} \tag{3-14}$$

is equivalent to (3-8), thus also equivalent to (3-3)–(3-5).

Then, if $\boldsymbol{\mu}^*$ is a solution point in (3-12)–(3-14), which is also an optimal dual for the balance constraint (3-4), then $\boldsymbol{\lambda}^* = \left\{\mu_j^* \frac{24}{|\mathcal{T}|}\right\}_{j=1}^{24}$ induces an economic equilibrium by the resulting construction of the feasible space (3-13)–(3-14). Hence, $\boldsymbol{\lambda}^* \in \Lambda$.

■

and a is a constant (deterministic value), then ρ_{θ_i} is translation invariant if $\rho_{\theta_i}(R + a) = \rho_{\theta_i}(R) + a$.

It is important to discuss two main aspects highlighted by Theorem 1.

First, an equilibrium price for the proposed hedging market can be straightforwardly computed following equation (3-6). It recovers the marginal impact in the overall (i.e., among all players) risk-adjusted spot-market clearing value (second term of (3-3)), similar to the standard uniform pricing framework, however, evenly spread over the 7 repeating hours of the week-ahead trading horizon (i.e., adjusted by a factor of $24/|\mathcal{T}| = 1/7$).

Second, the properties endowed and held by the market-clearing process (3-3)–(3-5) are similar to the decentralized, non-cooperative one. Note that the set of equilibrium prices and related quantities in (3-2) can be seen as a particular case of randomly negotiated equilibrium prices in a decentralized market. The particularization assumes that all bilateral trades have the same price per product. This situation is generally justified in steady-state market studies, where market participants face low transaction costs and market transactions are transparent. These assumptions make it reasonable to assume that bilateral transactions should not deviate much from each other.

Within this context, among all possible equilibria in (3-2), the one found in (3-6) is associated with the competitive equilibrium state, which enjoys relevant properties, such as those presented in Corollary 1, and is considered a benchmark reference for market assessments in various decentralized market studies.

We refer the interested reader to the discussions and references on the convergence of decentralized market results to the competitive equilibrium reference in (YANG; FUJISHIGE, 2017), and the application of this concept in the electricity market in (O'NEILL et al., 2005).

Next, we state and prove two desirable properties the proposed decentralized, competitive market endows (TANAKA; CONEJO; SIDDIQUI, 2022) as a corollary from Theorem 1.

Corollary 1 *Let a market-oriented mechanism be defined by a trading place where each player negotiates 24 simultaneous week-ahead forward contracts on hourly energy spot prices. If each market participant $i \in \mathcal{I}$ is characterized by a θ_i-parameterized coherent risk-measure-based preference functional ρ_{θ_i} and feasible trading set $\mathcal{Q}_i$, and the clearing quantities $(\boldsymbol{Q}_i^*)$ follows the solution of* (3-3)–(3-5) *with trading price $(\boldsymbol{\lambda}^*)$ defined by* (3-6)*, then we have*

1. ***Market Efficiency**: The overall welfare defined by* (3-15) *is maximized and no economic agent $i \in \mathcal{I}$ has incentive to deviate unilaterally from $\boldsymbol{Q}_i^*$.*

$$\sum_{i \in \mathcal{I}} \left[\rho_{\theta_i} \left(R_i \left(\boldsymbol{\lambda}^*, \boldsymbol{Q}_i^*, \tilde{\boldsymbol{G}}_i, \tilde{\boldsymbol{\pi}} \right) \right) \right] \tag{3-15}$$

2. ***Revenue Adequacy**: All transactions associated with the cleared quantities $\left\{ \boldsymbol{Q}_i^* \right\}_{i \in \mathcal{I}}$ can be settled at $\boldsymbol{\lambda}^*$ without any financial shortfall.*

Proof. The proof of **Market Efficiency** follows directly from Theorem 1. At $\boldsymbol{\lambda}^*$, on the one hand, the Lagrangian function (3-7), which recovers the overall welfare function (3-15), is maximized. On the other hand, $\boldsymbol{\lambda}^*$ is an economic equilibrium price, thus the optimal willingness-to-contract of all players $i \in \mathcal{I}$ is given by $\boldsymbol{Q}_i^*$.

To prove the **Revenue Adequacy**, note that at each hour $t \in \mathcal{T}$ of the week-ahead trading horizon, the financial transaction in the market due to a participant $i \in \mathcal{I}$ is given by

$$\left(\lambda_{h(t)}^* - \tilde{\pi}_t \right) Q_{i,h(t)}^*$$

By summing across all agents,

$$\sum_{i \in \mathcal{I}} \left[\left(\lambda_{h(t)}^* - \tilde{\pi}_t \right) Q_{i,h(t)}^* \right] = \left(\lambda_{h(t)}^* - \tilde{\pi}_t \right) \sum_{i \in \mathcal{I}} Q_{i,h(t)}^* = 0$$

since at $\boldsymbol{\lambda}^*$, the market is at an economic equilibrium.

■

Corollary 1 highlights that the proposed market mechanism has two desired properties:

1. It has an efficient point where the overall welfare is achieved, and each economic agent has its value within the market maximized; and
2. The total financial transaction due to the agents buying a contract for each hour of the week-ahead trading horizon is covered by the total financial transaction due to the agents selling the respective contract. Therefore, no financial shortfall occurs in the market.

In the next section, we present a numerical study to illustrate the potential of the proposed hedging mechanism using real data from the Brazilian power system and renewable agents.

4
Case Study

In order to analyze the potential benefits of the proposed hedging mechanism, in this section, we present a numerical experiment using real data from renewable power plants in the Brazilian power grid.

4.1
Experimental Setup Description

To empirically evaluate the benefits of the proposed hedging market mechanism, we select a total of $n = 28$ renewable power plants over the Brazilian territory, all connected to the main power grid, of which 13 are wind power plants, and 15 are solar. Aiming at a representative analysis, we selected the most resourceful regions of the country for each source. For the wind farms, 8 out of the 13 are located in the northeast of Brazil, and the remainder 5 are in the south. Similarly, for the solar power plants, 10 out of 15 are located in the northeast, and the remainder 5 are in the southeast. With respect to the long-term contracting involvement, we assume that each renewable agent has a signed long-term PPA with a consumer.

Because long-term PPA prices are not publicly available, to study the hedging effect of the proposed contracts, we set the long-term PPA prices equal to the average spot price (246.97 R$/MWh). PPA amounts, on the other hand, are typically sold close to their firm energy certificates, which are publicly available information. So, we define PPA amounts as each generator firm energy certificates.

All the details of each renewable power plant considered in this numerical experiment are presented in Table 4.1. Columns 1 and 2 indicate, respectively, the name of the power plant and its source type. In this study, we consider $\alpha_i = 0.95,\ \forall\ i \in \mathcal{I}$, with Column 3 of Table 4.1 displaying the values of β_i assumed for each renewable agent $i \in \mathcal{I}$. Column 4 highlights installed capacities, whereas columns 5 and 6 indicate the PPA volume and sales price due to each renewable agent, respectively. Finally, columns 7 and 8 display the State and Region in which they are located.

To characterize the uncertainty factors $\left(\tilde{\boldsymbol{G}}, \tilde{\pi}\right)$ affecting the decision problem, we follow the standard stochastic modeling approach and assume a probability space $\left(\Omega, \mathcal{F}, \mathbb{P}\right)$ with a finite sample set (plausible scenarios). A data-driven decision-making rationale is considered by assigning a collection of historical data to the set of scenarios, with the probability of occurrence

Table 4.1: Data and details of each renewable power plant considered in this numerical experiment.

Power Plant	**Source**	β	**Capacity** (MWh)	$\boldsymbol{V}$ (MWh)	$\boldsymbol{P}$ (\$/MWh)	**State**	**Region**
Caetité	Wind	95%	58.8	29.70	246.97	BA	NE
Cristalândia	Wind	80%	90.0	38.88	246.97	BA	NE
Cacimbas	Wind	75%	86.1	32.94	246.97	CE	NE
C. de Acarau I	Wind	70%	28.0	10.08	246.97	CE	NE
Icaraizinho	Wind	60%	54.6	18.68	246.97	CE	NE
Alegria I	Wind	50%	51.0	14.92	246.97	RN	NE
Calango I–III	Wind	25%	60.0	25.02	246.97	RN	NE
C. Voltalia	Wind	10%	108.0	51.39	246.97	RN	NE
Atlantica	Wind	10%	120.0	44.91	246.97	RS	S
Livramento	Wind	25%	163.2	75.68	246.97	RS	S
Xangri-lá	Wind	50%	31.7	9.27	246.97	RS	S
Água Doce	Wind	75%	129.0	34.67	246.97	SC	S
BJ. da Serra	Wind	95%	93.0	23.04	246.97	SC	S
Bom Jesus	Solar	25%	60.0	15.12	246.97	BA	NE
Ituverava	Solar	50%	196.0	52.92	246.97	BA	NE
Juazeiro Solar	Solar	55%	120.0	31.32	246.97	BA	NE
Lapa	Solar	60%	60.0	15.66	246.97	BA	NE
Calcário	Solar	70%	132.0	31.32	246.97	CE	NE
Sol do Futuro	Solar	75%	81.0	14.58	246.97	CE	NE
Rio Alto	Solar	80%	81.0	18.81	246.97	PB	NE
Fontes Solar I	Solar	85%	5.0	0.88	246.97	PE	NE
Nova Olinda	Solar	90%	210.0	55.44	246.97	PI	NE
Assu V	Solar	95%	30.0	8.28	246.97	RN	NE
Paracatu	Solar	25%	132.0	30.60	246.97	MG	SE
Pirapora	Solar	50%	329.0	76.68	246.97	MG	SE
Boa Hora	Solar	75%	145.1	32.22	246.97	SP	SE
Dracena	Solar	80%	81.0	15.93	246.97	SP	SE
Guaimbé	Solar	90%	150.0	26.55	246.97	SP	SE

evenly distributed among them. We gather hourly observed values of energy production for the renewable power plants considered in this experiment and the energy spot price of the four zones of the Brazilian system, spanning from 01-July-2019 up to 20-September-2021, thus with a total of 116 representative weeks. To clear the purely financial derivatives considered in this work, a reference price is derived based on the average of zonal spot prices.

Finally, in this experiment, we simplify the set of feasible contracting decisions $\mathcal{Q}_i$ of each renewable agent $i \in \mathcal{I}$ to allow only buy/sell strategies up to the amount of the respective long-term PPA volume. We also impose an additional condition that during daytime (i.e., $j \in \{7, \ldots, 18\}$), all solar power plants can only sell forward contracts in this hedging market, meanwhile during the hours without sunlight (i.e., $j \in \{1, \ldots, 6\} \cup \{19, \ldots, 24\}$), all solar power plants can only buy forward contracts. In this context, we restrict our analysis to potential market states associated with hedging conditions, mitigating the capability of renewable agents to purely trade or arbitrage in the market. For expository purposes, we denote by $\mathcal{I}_W = \{1, \ldots, 13\}$ and $\mathcal{I}_S = \{14, \ldots, 28\}$, with $\mathcal{I} = \mathcal{I}_W \cup \mathcal{I}_S$, the partitioning of the set of players in wind- and solar-powered plants, according to the sequencing presented in Table (4.1).

In the next subsection, the main numerical results and insights related to the proposed hedging mechanism are described and discussed.

4.2 Market Benefits in the Equilibrium

In this subsection, we showcase the benefits of the proposed week-ahead hedging mechanism using the experimental setup described in Section 4.1. We consider two different cases: the hereinafter called **Case 1**, where the renewable agents do not have access to the market, thus their net revenue stream comes only from the long-term PPA, and **Case 2**, in which the hedging market is available to all participants.

A general criterion to evaluate the potential benefit of the proposed hedging mechanism is its impact on the overall market welfare, computed by (3-15). In Table 4.2, this metric for both contexts, when the market is not available (**Case 1** – Column 2) and when it is available (**Case 2** – Column 3), is showcased along with their relative difference (Column 4).

Based on the previously presented data from the Brazilian power system and the representative collection of renewable agents, we observe an increase in welfare equal to 9.5%.

Table 4.2: Overall Welfare ($kR\$$) by (3-15) for **Case 1** (without hedging market) and **Case 2** (with hedging market)

	w\out Hedging Market ($kR\$$)	**with Hedging Market** ($kR\$$)	**% Difference**
Overall Welfare	$23,939.83$	$26,213.80$	9.50%

Furthermore, we can infer the specific benefit for each renewable agent due to the capability of hedging their financial operations in the proposed week-ahead market. Similar to Table 4.2, in Table 4.3, we present the certainty equivalent cash flow value (ρ_{θ_i}) for each agent $i \in \mathcal{I}$ in both **Case 1** (Column 2) and **Case 2** (Column 3), along with the relative increase in value (Column 4). We note that the percentage benefit of **Case 2** compared to **Case 1** can reach relatively high levels, in some cases, higher than 100%, i.e., doubling the business value for the renewable agent. In fact, the overall increase on average is roughly 30%, with approximately 20% for wind farms and 36% for solar plants, highlighting the potential of the hedging mechanism.

Figure 4.1 depicts the individual certainty equivalent gains (from **Case 1** to **Case 2**) per unit of risk faced by each agent in **Case 1**, defined as $\mathcal{R}(R_i) = \mathbb{E}(R_i) - \text{CVaR}_{\alpha_i}(R_i)$. We find empirical evidence of an increasing hedging effect, i.e., in the equilibrium, agents facing higher risk levels tend to collect more benefits from the proposed product.

Table 4.3: Certainty-equivalent cash-flow value (ρ_{θ_i}) for each agent $i \in \mathcal{I}$ in both **Case 1** and **Case 2** (k\$).

	Certainty Equivalent (ρ)		
Power Plant	**w\out Hedging Market** ($kR\$$)	**with Hedging Market** ($kR\$$)	**% Difference**
Caetité	244.41	458.44	87.57%
Cristalândia	796.49	882.15	10.75%
Cacimbas	732.13	848.69	15.92%
C. de Acarau I	272.73	278.71	2.20%
Icaraizinho	547.33	560.72	2.45%
Alegria I	509.98	524.89	2.92%
Calango I–III	1,006.22	1,043.87	3.74%
C. Voltalia	2,382.67	2,639.02	10.76%
Atlantica	2,053.44	2,173.65	5.85%
Livramento	2,372.91	2,417.37	1.87%
Xangri-lá	277.53	285.22	2.77%
Água Doce	836.37	889.13	6.31%
BJ da Serra	-294.64	17.46	105.92%
Bom Jesus	577.66	594.94	2.99%
Ituverava	1,192.08	1,454.23	21.99%
Juazeiro Solar	1,198.11	1,220.69	1.88%
Lapa	401.02	491.81	22.64%
Calcário	945.32	1,059.58	12.09%
Sol do futuro	589.00	635.39	7.87%
Rio Alto	491.19	510.95	4.02%
Fontes solar I	1.91	9.71	409.51%
Nova olinda	548.81	852.94	55.41%
Assu V	243.23	253.56	4.25%
Paracatu	1,212.15	1,230.27	1.50%
Pirapora	3,103.21	3,147.02	1.41%
Boa hora	434.09	454.75	4.76%
Dracena	418.80	427.29	2.03%
Guaimbé	845.67	851.34	0.67%

Furthermore, Figure 4.2 illustrates individual and block-average certainty equivalent gains (from **Case 1** to **Case 2**) for Wind Power Plants per correlation level between hourly generation and spot price. Such a metric aims to quantify the price-and-quantity risk for future scenarios within the contract horizon. It is constructed by averaging the lowest 10% of hourly correlation coefficients across all scenarios, with each coefficient calculated throughout the contract horizon (one week) for a given scenario.

We can see that the lower the correlation metric between hourly generation and price (a measure of price-and-quantity risk level), the higher the benefits wind power plants collect from the hedging market in terms of certainty equivalent.

4.3
Market Equilibrium Analysis

In Figure 4.3, the resulting equilibrium price for each hourly forward contract is presented. We observe that the equilibrium of the hedging price follows similarly to the typical dynamics of the energy spot price along the hours: low levels in the first hours of the day, then increasing its value up to

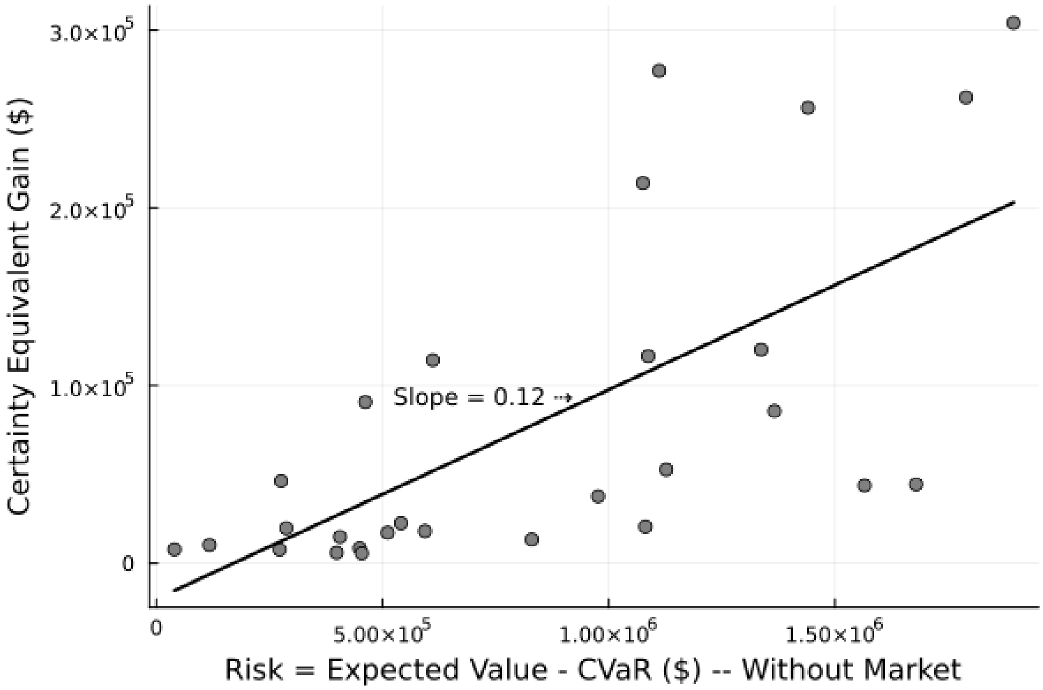

Figure 4.1: Individual certainty equivalent gains (from **Case 1** to **Case 2**) per unit of **Case 1**'s risk.

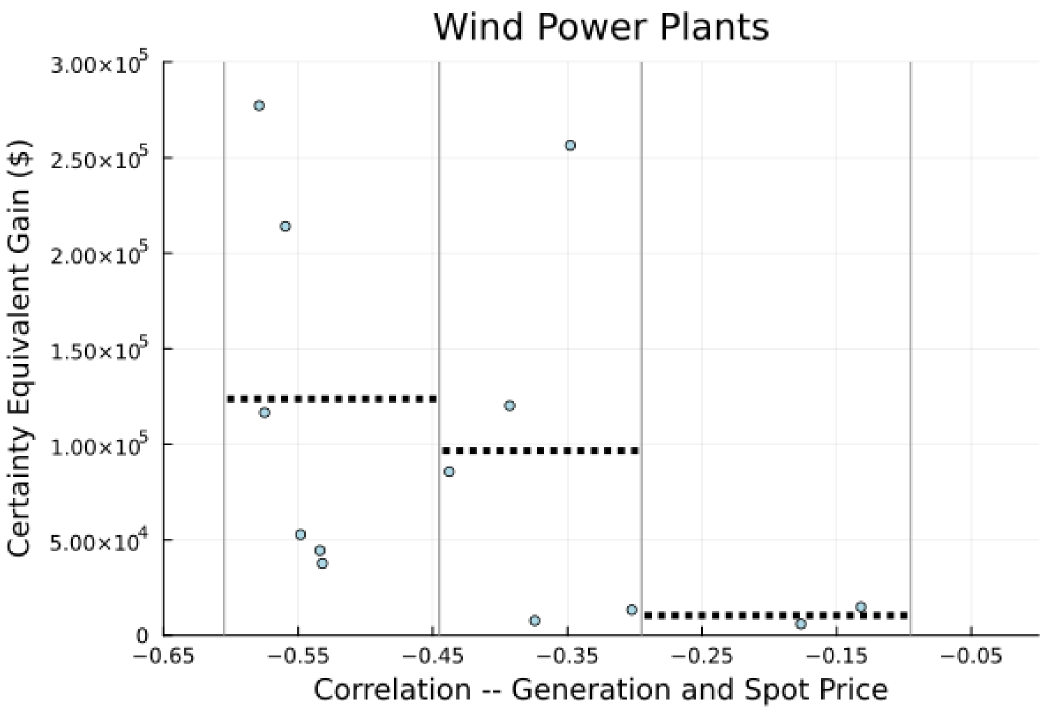

Figure 4.2: Wind power plants' individual and block-average certainty equivalent gains (from **Case 1** to **Case 2**) as a function of the correlation of their generation with spot prices.

the peak operating hours, then reducing it after on.

Additionally, in Figure 4.4, we present the total amount of hedging contracts sold (bought if negative) in the equilibrium by each renewable source (Wind and Solar) in each hour discriminated by region (Wind – NE, Wind – S, Solar – NE, and Solar – SE). Except for 7 and 8 am, solar power agents buy contracts for hedging during the nighttime and sell them in the remaining hours. On the other hand, wind power plants buy and sell hedging contracts in opposite directions compared to their solar counterparts, highlighting the complementary value of the mechanism.

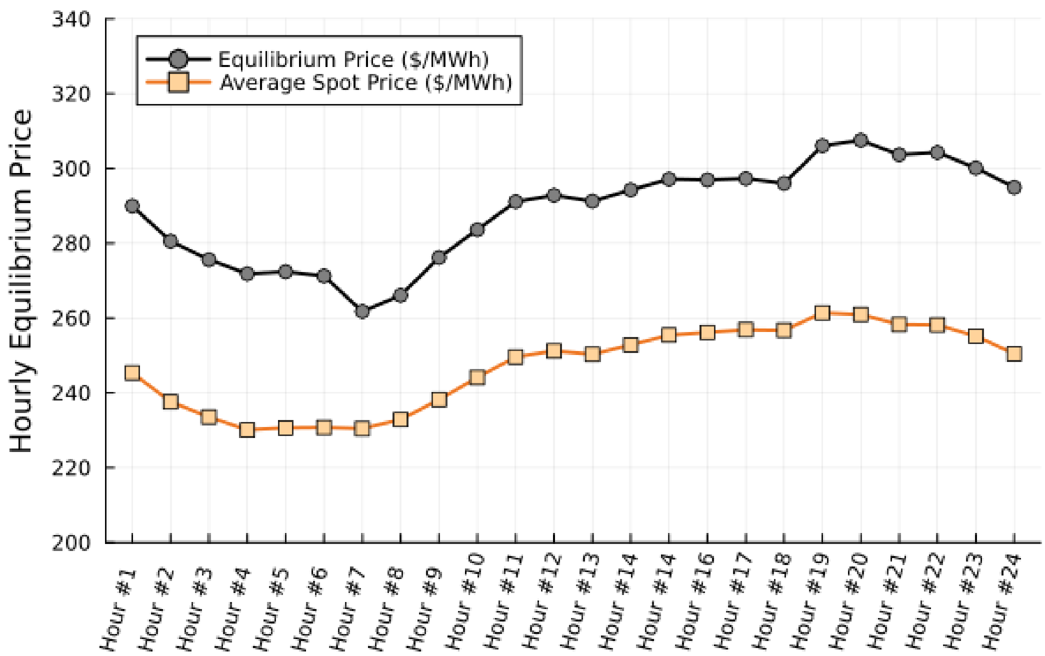

Figure 4.3: Equilibrium price ($/MWh) for each hourly hedging contract along with the 24-hour average spot price profile.

We particularly highlight four disjoint periods:

1. The first one, for $j \in \{1, \ldots, 6\}$, i.e., in the dawn, the willingness-to-contract in the market is the highest observed due to, essentially, the total absence of solar power production, a surplus of wind-power generation in the northeast, and the lowest level of energy spot prices;

2. Secondly, for $j \in \{7, 8\}$, only wind farms trade in the market, with the ones in the northeast (NE) selling to those in the south (S). This also results in the lowest equilibrium prices observed in Figure 4.3;

3. Then, for $j \in \{9, \ldots, 18\}$, the trading dynamics are reversed, with solar power plants selling hedging contracts to wind plants with an increasing

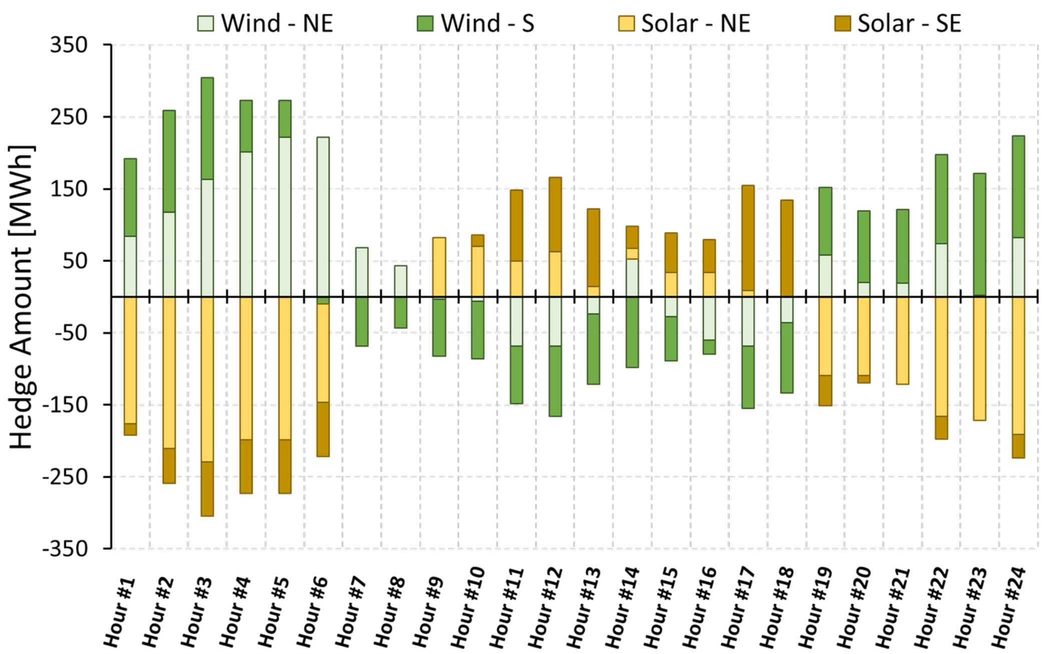

Figure 4.4: Total equilibrium quantity contracted (avgMW) by each renewable source (Wind and Solar) and Region: Wind – NE (light green), Wind – S (green), Solar – NE (light yellow), and Solar – SE (yellow).

equilibrium price. This effect can be explained by the significant shortfall in overall wind power production (see Figure 1.2) and higher spot-price levels, which increases the price and quantity risk level; and

4. Finally, for $j \in \{19, \ldots, 24\}$, the equilibrium showcases wind power plants selling contracts back to solar units at high prices due to the increased price-and-quantity risk faced by solar units during the night-time.

Note that, differently from the dawn ($j \in \{1, \ldots, 6\}$), wind farms in the south are the majority in trading during this final period.

To illustrate the equilibrium result for a wind and solar power plant, Figure 4.5 and Figure 4.6 present for *Caetité* (Wind Power Plant) and *Dracena* (Solar Power Plant), respectively, for the first 24 hours of the weekly contract, the generation profiles, and the final hourly forward position decomposed as long-term PPA and hourly hedging contracts. It is clear that the final amount of forward contracts sold (flat PPA plus hourly contracts) is, in general, adjusted to follow the generation profile and reduce the price-and-quantity risk. Nevertheless, the complementarity between sources plays a relevant role in this hedging market.

Note that the hourly contract prices in Figure 4.3 are higher than the long-term PPA price (246.97 R$/MWh), indicating a risk premium. When risk-averse wind power generators face low generation profiles during the day, they have incentives to reduce their forward position, purchasing in the hourly hedging market by a price higher than the price of their long-term PPA, to mitigate the price-and-quantity risk. On the other side, solar generators profit from selling these hourly contracts and use this profit to implement a similar hedging strategy during the night. So, the 16.8% spread of the average hedging prices (288.44 R$/MWh) over the long-term PPA contract price (246.97 R$/MWh) indicates a positive risk premium.

Despite this positive risk premium, solar and wind power generators agree to exchange excesses and deficits through hourly contracts and still improve their certainty equivalent levels. These results provide relevant evidence that adding a new hedging market enabling Brazilian renewable generators to adjust their hourly exposure to the spot market should have non-negligible benefits.

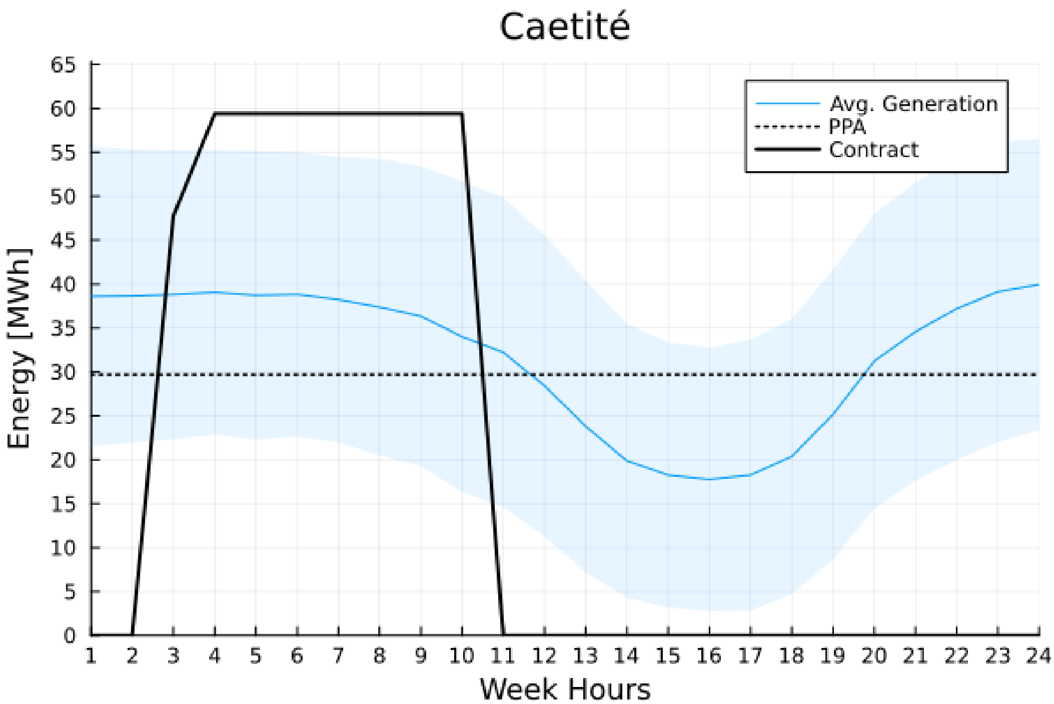

Figure 4.5: First 24 hours of the weekly contract with the generation profile, and final hourly forward position decomposed as long-term PPA and hourly hedging contracts for *Caetité* (Wind Power Plant).

4.4 Sensibility in Long-Term Contracting Levels

To further explore and quantify the potential of the proposed hedging mechanism, we perform a sensibility analysis of the long-term contracting levels. For this purpose, we vary the forward involvement level, by scaling the

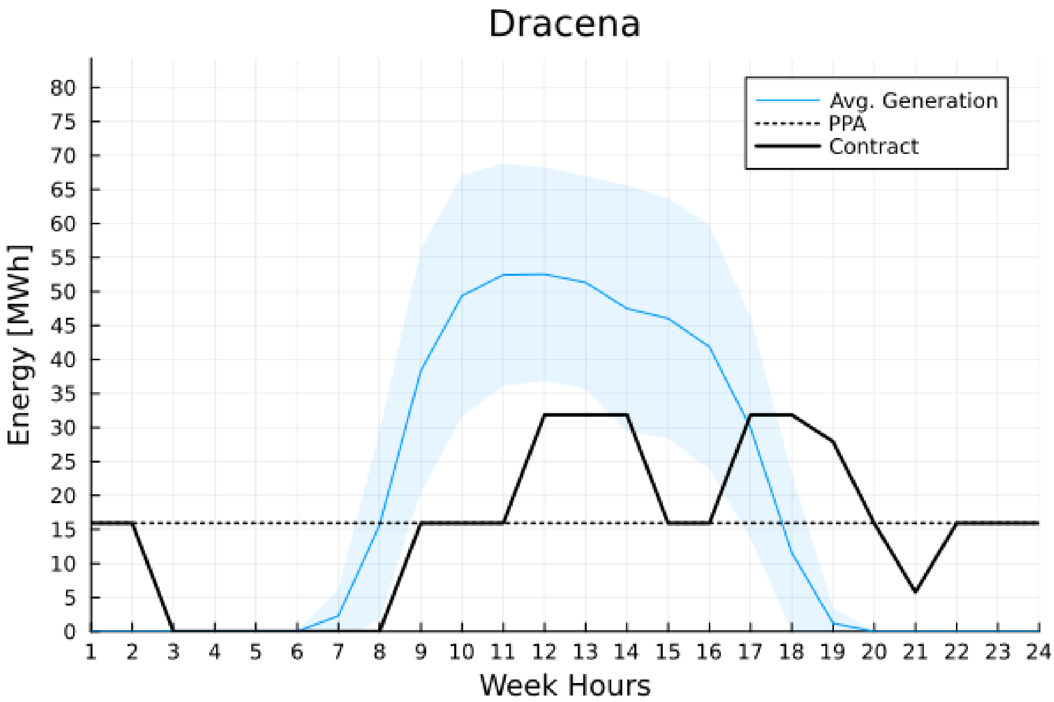

Figure 4.6: First 24 hours of the weekly contract with the generation profile, and final hourly forward position decomposed as long-term PPA and hourly hedging contracts for *Dracena* (Solar Power Plant).

PPA volume (V_i) of each player $i \in \mathcal{I}$ (see Column 5 of Table 4.1) by a factor γ, and observe the impact on both the overall welfare and the equilibrium prices.

Figure 4.7 showcases the overall welfare (gray area) of **Case 1** and **Case 2**, similar to Column 2 and Column 3 in Table 4.2, along with the minimum, average, and maximum equilibrium price values (lines) for a range of long-term contracting (PPA) levels $\left\{\gamma V_i\right\}_{i \in \mathcal{I}}$ for $\gamma \in \left[0\%, 150\%\right]$. The light dot indicates the point where the base case used in previous analyses stands for, i.e., $\gamma = 100\%$.

Note that for the range of contracting levels $\gamma = [10\%, 125\%]$, the overall welfare in **Case 2** is higher than the welfare in **Case 1** at the base case (i.e., for $\gamma = 100\%$). Essentially, this result indicates that the renewable agents can increase by roughly 25% their supply offer in long-term PPAs to consumers and still recover a higher welfare value at the economic equilibrium if the proposed hedging market is available for negotiating.

Moreover, we observe that the difference in the overall welfare between **Case 1** and **Case 2** is minimum (relative gain equal to 4.5%) on $\gamma = 60\%$, where the long-term forward market has the maximum welfare.

Finally, we highlight that the magnitude of the average equilibrium prices increases with the levels of γ. This happens because as we increase the overall forward involvement, the price-and-quantity risk also increases, thereby

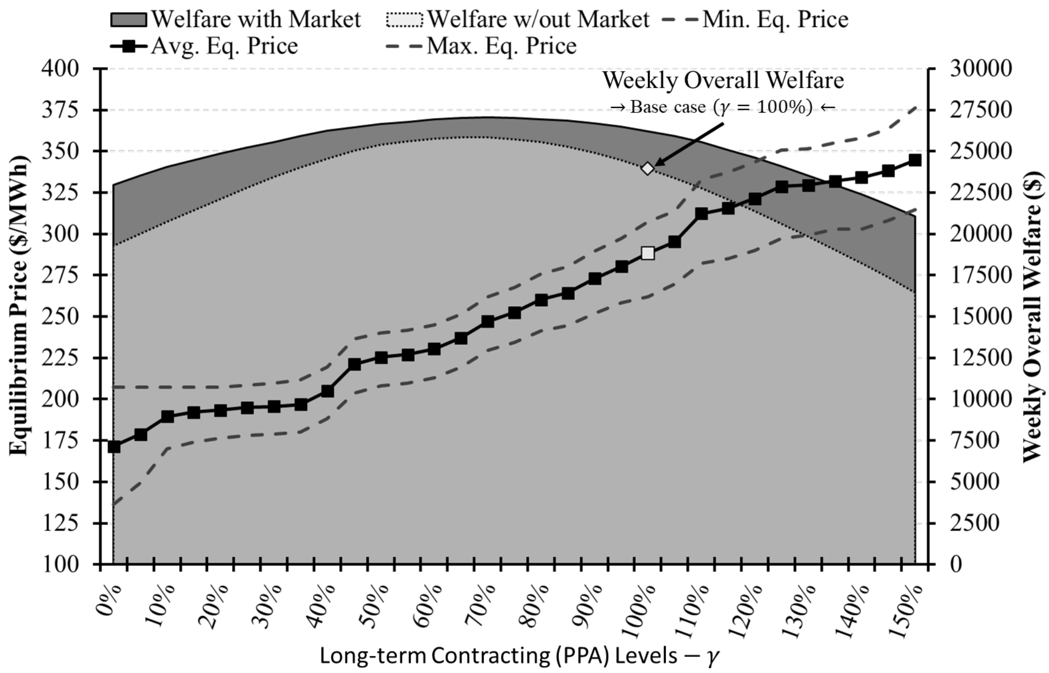

Figure 4.7: Welfare of **Case 1** and **Case 2** and minimum, average, and maximum equilibrium prices for a range of long-term contracting (PPA) levels.

elevating the value (price) of the hedging market.

5
Conclusions

In this work, we study and analyze a market-oriented hedging mechanism for renewable agents. More specifically, we propose a decentralized week-ahead market where participants can trade forward contracts for delivery at specific hours of the day.

This mechanism aims to enable Brazilian renewable agents to compatibilize their generation profiles with a long-term forward-oriented market that currently does not acknowledge their intra-day generation profile.

Based on that, Brazilian renewable agents can adjust their contracting levels according to their generation and risk profiles, thus minimizing the exposure to the price-and-quantity risk through a pure financial market mechanism.

Two technical results are stated and proved: (i) an equivalent mathematical-programming-based formulation to identify an economic equilibrium state along with a rationale to compute the associated equilibrium prices; and (ii) two desirable market properties the proposed decentralized, competitive market endows, i.e., *Market Efficiency* and *Revenue Adequacy*.

Within the limitations of the assumptions and data used in this dissertation, which include spot price and renewable generation forecast accuracy, the long-term PPA equilibrium conditions, and the risk attitude of market participants, the results and analyses developed based on the equilibrium point estimated in our case study section allow us to convey the following remarks:

1. For the 28 representative wind and solar power plants, a relative welfare increase of 9.5% is estimated;

2. The certainty-equivalent value of all agents increases; in some cases, more than 100%. The overall increase on average was roughly 30%, with approximately 20% for wind power plants and 36% for solar power plants;

3. By comparing the certainty equivalent with and without the proposed hedging instruments, results show higher benefits for renewable agents previously exposed to higher price and quantity risk;

4. Results also indicate that by considering the hedging instrument, the forward involvement could be elevated 25% and still keep the same welfare of the base case without the hedging market. Analogously, it may also enable over-contracted renewables to keep their position on

the long-term forward market with reduced risk, thereby promoting a sustainable and more robust market environment; and

5. Finally, market equilibrium results showcase a positive risk premium and highlight the relevance of the complementarity between wind and solar generation profiles in Brazil, with solar power plants covering wind generation during the day and wind generators doing the same for solar units during nighttime.

The equilibrium state estimated in this thesis, using representative historical data that reflects a given market circumstance, serves as a relevant yet static benchmark for a market condition that is inherently dynamic. However, we argue that the importance of hourly-granular forward instruments, which extract value from complementary renewable resources, should increase as solar integration is projected to rise in the coming years in Brazil.

Based on the conclusions drawn above, results provide relevant evidence that Brazilian renewable agents should collect non-negligible benefits from a new hourly-based hedging market, which can be seen as a step forward in developing the forward market in this country.

The benefits observed in our experiments explore the complementarity of Brazilian renewable generation profiles and the diversity of risk aversions of renewable agents to complement the traditional local forward market. Hence, although our results are case-dependent, they should be of interest to any country where renewables trade (or are willing to trade) long-term forward contracts.

Notwithstanding, the interaction of such new products, which can be seen as mid-term hedging, should be adapted and evaluated under each market context, structure, and agents' information level. For instance, in the presence of two-settlement bid-based markets, where renewables can adjust their forward position daily, the proposed contracts could enable them to modulate their forward hourly profile months or years ahead, reducing the exposure to short-term prices. Therefore, exploring the applicability of the proposed instrument, or its variants, to other market structures constitutes a relevant future research topic.

Finally, the equilibrium and the resulting hedging benefit of the proposed contracts rely on the forecast capacity of each agent. In line with modern *application-driven learning* works (see (GARCIA et al., 2021) and (DVORKIN, 2024)), this opens relevant and interesting research questions regarding the study of the best forecast model that internalizes this specific application outcome.

6
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