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Pontifícia Universidade Católica
do Rio de Janeiro

Pedro George Prescott Ferraz

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

Dissertação de Mestrado

Dissertation presented to the Programa de Pós–graduação em 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

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

Luiz Augusto Barroso
PSR

Prof. Bruno Fânzeres dos Santos
Departamento de Engenharia Industrial – PUC-Rio

Franklin Kelly Miguel
Companhia Paranaense de Energia

Rio de Janeiro, April the 27th, 2023

Pedro George Prescott Ferraz

Pedro George Prescott Ferraz received his B.Sc. degree in Electrical Engineering in 2008 from the Universidade de Brasília, Brazil. In 2018, received a diploma of the Florence School of Regulation-FSR, in Florence/Italy, for the Annual Training on Regulation of Energy Utilities. He has worked in Brazilian Power System since 2009.

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Abstract

Prescott, Pedro; Street, Alexandre (Advisor). **On the Regulatory and Economic Incentives for Renewable Hybrid Power Plants in Brazil**. Rio de Janeiro, 2023. 59p. Dissertação de Mestrado – Departamento de , Pontifícia Universidade Católica do Rio de Janeiro.

The complementarity between renewable generation profiles has been widely explored in literature. Notwithstanding, the regulatory and economic frameworks for hybrid power plants add interesting challenges and opportunities for investors, regulators, and planners. Focusing on the Brazilian power market, this paper proposes a unified and isonomic firm energy certificate (FEC) calculation for non-controllable renewable generators, which allows us to 1) generalize the FEC concept for hybrid units and 2) capture the regulatory and economic synergies between sources. Based on the non-discriminatory FEC proposed for hybrid power plants, the co-optimization of both forward-market and network-access contracting strategies is studied, and its economic incentives are demonstrated. The optimal share of renewable sources composing the hybrid power plant is also considered in the model and analyzed in our case studies. Based on real data from the Brazilian power market, we quantify the benefits of the proposed market structures and model for a typical wind–solar hybrid unit.

Keywords

Hybrid power plants; Renewable Generation; Firm Energy Certificate; Network-access Contract; Risk Management; Stochastic Programmin.

Resumo

Prescott, Pedro; Street, Alexandre. **Incentivos Regulatórios e Econômicos para Usinas Híbridas Renováveis**. Rio de Janeiro, 2023. 59p. Dissertação de Mestrado – Departamento de , Pontifícia Universidade Católica do Rio de Janeiro.

A complementaridade entre os perfis de geração renovável tem sido amplamente explorada na literatura. No entanto, as estruturas regulatórias e econômicas para usinas híbridas de energia apresentam desafios e oportunidades interessantes para investidores, reguladores e planejadores. Focando no mercado de energia brasileiro, este artigo propõe um cálculo unificado e isonômico de Garantia Física (GF) para geradores renováveis não controláveis, que nos permite 1) generalizar o conceito de GF para unidades híbridas e 2) capturar as sinergias regulatórias e econômicas entre as fontes. Com base na GF não discriminatória proposta para usinas híbridas de energia, a co-otimização das estratégias de contratação de energia no mercado de futuro e da rede, o Montante de Uso do Sistema de Transmissão (MUST), é estudada, e seus incentivos econômicos são demonstrados. A participação ótima de fontes renováveis que compõem a geração da usina híbrida também é considerada no modelo e analisada em nossos estudos de caso. Com base em dados reais do mercado de energia brasileiro, quantificamos os benefícios das estruturas e modelos de mercado propostos para uma unidade híbrida típica de eólico-solar.

Palavras-chave

Usinas Híbridas; Geração Renovável; Garantia Física; Montante de Uso do Sistema de Transmissão; Gerenciamento de Risco; Programação Estocática.

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1
Introduction

Brazil has one of the most renewable generation fleets [1] in the world. However, it is a latecomer in contrast to the US and EU in the installation of wind, solar, and hybrid generation. Interestingly, hybrid generation units have been provingto be an effective way to reduce the intermittence of non-controllable renewable generation (see [2]) and, consequently, have the potential to increase renewables' firm energy production. The complementarity between solar and wind generation in Texas (US) has been studied in [3], wherein relevant gains in the firm supply capacity were found from paring both sources. In the energy transition context, renewable sources, not only in Brazil, have been demanding a great effort from both the academy and industry sides to address the increasing grid congestion and detrimental effects on reliability due to intermittence on the operational, planning, and market sides (see [4], and [5] for further reference). Although the complementarity between renewable sources has demonstrated to be economically beneficial in many situations, as will be further illustrated, the regulatory and market design rules for hybrid units may interact with these benefits.

The economic viability of hybrid renewable generation in Brazil mainly relies on two key and opposite forces, namely, 1) the risk-adjusted maximization of forward and spot market revenues and 2) the minimization of regulatory expenses with network-access contract (NAC) payments, which applies to all agents connected to the transmission system and, in the case of generators, is charged per maximum MW injected per month in the network. NAC's are mainly used to share transmission costs among generation and consumers while signalizing through locational tariffs expansion needs [6]. For the interested reader, we refer to [7] and [8] for a detailed discussion on the network access charges in Brazil for the demand side. Thus, the challenge is that both forces are directly affected by the firmness resulting from the complementarity between the sources being combined to form the hybrid power plant.

Within this context, the advantages of combining renewables in a portfolio of complementary sources to back long-term forward contract sales have been demonstrated in several papers for the Brazilian power system. In [9], for the first time, complementary renewable sources, namely, a biomass unit and run-of-riven small hydro, were combined through a risk-constrained optimized portfolio to mitigate the price-and-quantity risk and back a forward contract sale in the free trading forward market. In [10], the complementarity and risk-mitigation benefit of a large set of renewables coordinated in a single renewable pool to sell contracts in the market with lower risk was studied. More specifically, an allocation rule to distribute the shares among the renewables participating in the pool was devised based on the nucleolus of a stochastic cooperative game. In [11], the complementarity of renewables was also studied in the presence of different markets and contract formats. Finally, more recently in [12], forward contracts and call options were used to mitigate the price-and-quantity risk in complementary portfolios of renewables considering the ambiguity oven the probability distributions. Therefore, the complementarity of renewables in the various time scales and market structures is a key factor in fostering the sustainable integration of large shares of renewables.

Notwithstanding, the regulatory framework for hybrid generation in Brazil, as well as in other developing countries, is still under development (see the preliminary discussions in [13], [14] and [15]). None of the previously reported work deals with the regulatory benefits of the hybridization of complementary generation, such as wind and solar, considering the interactions between forward and network-access contracts as happens in Brazil. In this case, hybridization allows us to define a single regulatory FEC and a single NAC for the two complementary sources composing the hybrid power plant based on the final generation output. As the FEC limits the maximum amount of forward contracting and the NAC limits the FEC (as further explained in the next sections), hybrid units may benefit from jointly defining the two contracting strategies to maximize profits. Additionally, the recent update in the Brazilian regulatory framework allowed hybrid power plants to reduce NAC amounts. This regulatory act potentialized the benefits of co-optimizing network-access and forward contracts while creating an interesting link between transmission and renewable generation expansion.

The Brazilian concept of FEC for non-controllable renewable generation (wind, solar, biomass, and small run-of-the-river hydros) lacks uniformity. Yet, the generation constrained-off because of grid congestion has not been properly addressed[1]. The situation is especially relevant for hybrid power plants, which can adjust the maximum NAC amount (M) according to generation characteristics (we refer to [13] and [17]. The amount M defines the maximum power that a generating unit can inject into the network (measured as the average injected energy within short time intervals). Thus, the generator

[1]For the interested reader, we refer to the local regulation [14] and [16]

curtails all the generation above this value or a penalty of three times the NAC tariff is applied. However, the absence of uniformity on the definition of FEC among renewables and on how this relevant regulatory stamp is affected by M in the case of hybrid units challenges the regulatory framework. It weakens the economic incentives for the development of hybrid units in Brazil [18].

Objective and contributions

The objectives of this paper are threefold: 1) to define a non-discriminatory FEC calculation methodology for hybrid power plants in Brazil, 2) to propose a co-optimization model to define the optimal forward and network-access contracting strategies for a renewable risk-averse hybrid power plant, and 3) to study the optimal share of renewable sources composing the hybrid power plant. In this context, the contributions of this dissertation are the following:

1. A unified methodology to calculate the FEC of non-controllable renewable units that is consistent with the more general hybrid power plant FEC proposed in this work.

2. An analytic tool for generation companies and system entities (planner, operator, and regulator) to simulate the complementarity benefits that hybrid power plants may provide on i) the price-and-quantity risk mitigation, ii) the reduction of network costs, and iii) the potential and typical shares of renewable sources on future hybrid units.

The above contributions are studied and corroborated with real data from the Brazilian power system.

This document is structured as follows: Chapter 2 covers the nomenclature and data framework used in this work. In Chapter 3, we explore the complementarity of sources and the growing competitiveness of renewables in the energy transition context. We also investigate the development of hybrid renewable power plants. Chapter 4 examines the regulatory framework for firm energy certificates (FEC) and the regulatory gap regarding the methodology for hybrid power plants. This chapter also introduces an important regulatory piece regarding the evolution of network-access contracts (NAC) in Brazil and the generation curtailment specifically applied to renewables.

The core of this work is presented in chapters 5 and 6. In chapter 5, we introduce a unified FEC concept, called TEV-FEC, for non-controllable renewable sources that can accommodate 1) the hybridization of different sources, 2) the capture of complementarity synergy among them, and 3) the effect of NAC.

Chapter 6 presents a comprehensive approach that accounts for both revenue and risk considerations; the proposed co-optimization model can help generators to make more informed decisions about their contracting strategies and ultimately increase the profitability and sustainability of their renewable power plants. This co-optimization model helps generators make more informed decisions about their contracting strategies, ultimately increasing the profitability and sustainability of their renewable power plants.

Chapter 7 presents case studies that provide insights into the benefits and limitations of the proposed methodology, as well as demonstrate its practical applications in real-world contexts. Finally, in Chapter 8, we summarize the main conclusions of this work and highlight future extensions.

2
Nomenclature and Data

In this chapter, we introduce the key concepts, nomenclature, and data related to renewable generation and prices that will be used throughout the case studies presented in this work. By establishing a clear understanding, we can provide valuable context and foundation used in case studies further presented in this work.

2.1
Nomenclature

The nomenclature was specially designed for the co-optimization model of forward and Network-access contract (NAC) contracting presented in Chapter 6.

Concepts

– **Hybrid Power Plant**: a power plant composed of two or more generation sources that inject together power on the same grid's spot.

– **Network-Access Contract (NAC)**: the maximum value of demand of grid or transmission that the generator can inject into the power system or the consumer can demand instantly. The term corresponds to "Montante de Uso do Sistema de Transmissão" (MUST) adopted in the Brazilian power system.

– **Curtailment**: curtailment is the deliberate reduction in output of generation below which could have been produced in order to balance energy supply and demand or due to transmission constraints when generation surpasses the NAC.

– **Forward contract (Q)**: is a fixed-term contract between two parties for the delivery of a certain amount of energy. The buyer undertakes to buy an agreed amount of energy for the agreed period, paying the agreed price (p) on the date specified in the contract. This product is directed towards retailers, providers of renewable energy, and producers and provides price risk cover.

– **Firm energy certificate (FEC)**: the maximum value of energy that a power plant can sell in forward contracts that corresponds to "garantia física", a term used in the Brazilian power system.

Sets and Indices

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

Random variables

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

Constants and parameters

- c Network-access contract tariff (R\$/MW per month).
- C^S Investment expenditure CAPEX on solar installed capacity (\$/MW).
- C^W Investment expenditure CAPEX on wind installed capacity (\$/MW).
- p Forward contract price (\$/MWh).
- η Penalty for network-access contract violations.
- ϵ Upper tolerance for network-access contract violation.
- α CVaR confidence level (risk-aversion parameter).
- λ CVaR weight (risk-aversion parameter).
- G_t^S Historical generation data of the solar generator for hour $t \in \mathcal{H}$ (MWh).

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

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

Decision Variables

M Network-access contract quantity amount (MW).

Q Forward contract quantity amount (MWh).

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

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

Functions

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

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

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

2.2 Data and uncertainty representation

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

It is significant to mention that the historical generation availability, defined as the generation given the resource availability disregarding curtailments, might not be observable in some cases. For instance, new projects with no historical generation data or existing units that are subject to systematic curtailments constitute relevant examples. In this case, methods to create synthetic historical generation [19] data are often used by certification companies and generation companies. In this work, the generation availability is assumed as an input, and the methods used to generate synthetic historical data (if needed), despite impacting the final results, are out of the scope of this dissertation. However, as the inputs of any data-driven regulatory metric may have a significant impact on agents, standards and procedures should be determined to ensure isonomy.

The uncertainty of the future generation of the hybrid power plant and spot prices is modelled, in this work, through a non-parametric Bayesian network model and a sample of scenarios is generated through a Monte Carlo simulation [20]. To account for the cross-dependency between renewable generation and spot prices, we simulated 200 coupled scenarios for the three-dimensional time series comprising the spot prices, wind generation, and solar generation for every hour in $\mathcal{T}$. To do that, we used the commercial hydrothermal dispatch model SDDP (from PSR Consulting) to simulate Brazilian spot prices based on the scenarios for the main renewable spots of the Brazilian system, including the solar and wind generation studied in this dissertation. We selected the year 2025 as the target year for the contracting horizon $\mathcal{T}$. Finally, the simulated scenarios, represented by the sample-space set Ω, will be used as inputs in the risk-adjusted two-stage stochastic model presented in Chapter 7.

3
General aspects of Hybrid Generation

This chapter is meant to introduce hybrid power plants and their role in the regulatory landscape, including the complementarity of generation sources and the increasing competitiveness of renewables regarding the energy transition and development of renewable hybrid power plants.

Definition

The term *hybrid*, as proposed in this work, is a power generation facility that consists of two or more different sources of energy production, injecting power into the same grid spot. For a more detailed discussion of the various levels of source combination, technical reports produced by EPE ("Empresa de Pesquisa Energética" in Portuguese) can be checked [14]. In the context of this work, a hybrid power plant can refer to a range of facilities, including both new (greenfield) and existing (brownfield) generation sources, or a combination of the two, with full or partial integration of investment in generation sources and grid connection. The only requirement for a facility to be considered a hybrid power plant is that all sources of energy production share the same network-access contract (NAC).

As will be seen later on, our analyses focus on a specific type of hybrid power plant, which combines both wind and solar sources, remarked by competitive development recently and considerable complementarity on generation. It is essential to note that these sources are typically not dispatched by the System Operator (SO), and environmental conditions heavily influence their intermittent generation.

International State of Art

International experience with hybrid power plants has demonstrated that, despite their potential benefits, there are significant commercial and regulatory challenges to implementing them. Many of the projects built so far have relied on specific subsidies or regulations that favor them, and in some cases, these benefits have been challenged [21]. The motivation for hybrid projects varies depending on the specific conditions of each electrical system. For example, in India, the primary motivation for hybridizing is the lack of available land for both renewable installations and the expansion of transmission and distribution systems. Hybrid power plants are one of the strategies being considered to allow for the expansion of renewable capacity and the achievement of India's goals. In other countries which were studied, the primary goal is to take advantage of the possible synergies between different energy sources to improve the competitiveness of renewable energies.

Notwithstanding, it is important to note that the regulatory framework for hybrid generation in Brazil, as well as in other developing countries, is still in process of being developed (preliminary discussions can be found in [13], [14], and [15]). Despite this, the potential benefits of hybrid power plants in these regions have spurred interest and investment from both regulators and private entities.

Complementarity of generations

In 2017, the EPE [22] analyzed complementarity within data of wind speed and solar irradiation in five (5) locations in the Northeast of Brazil, showing promising results of the combination of these two sources. Later, in the EPE's Workshop of 15th May 2019, the MRTS consulting presented wind-solar hybrid projects in ten (10) different locations also in Northeast of Brazil, [23], pointing to the benefits of a new regulation which allows gains regarding the complementarity of sources. Thus far, a detailed analysis of complementarity in Northeast Brazil is found in [24].

In Texas (US), the complementarity between solar and wind generation has been studied in [3], wherein relevant gains in the firm supply capacity were found from paring both sources.

We emphasize that the complementarity should be considered in different time periods, including the short-term (intra-day), medium-term (months), and long-term (years). The negative correlation of generation in the short term is significant for reducing the cost of network-access contracts, while the complementarity between sources in the medium and long term can have a positive effect on the risk of the generation portfolio.

Renewables Competitiveness

In the context of the energy transition, which is accompanied by a global effort to reduce greenhouse gas emissions and address climate change, renewable energy sources, particularly wind and solar, have become increasingly competitive in many countries. The weighted-average levelized cost of electricity (LCOE) of wind and solar has been declining over the years, as illustrated in Figure 3.1 and Figure 3.2, respectively. For example, in Brazil, the cost of wind energy decreased by 68% between 2000 and 2019.

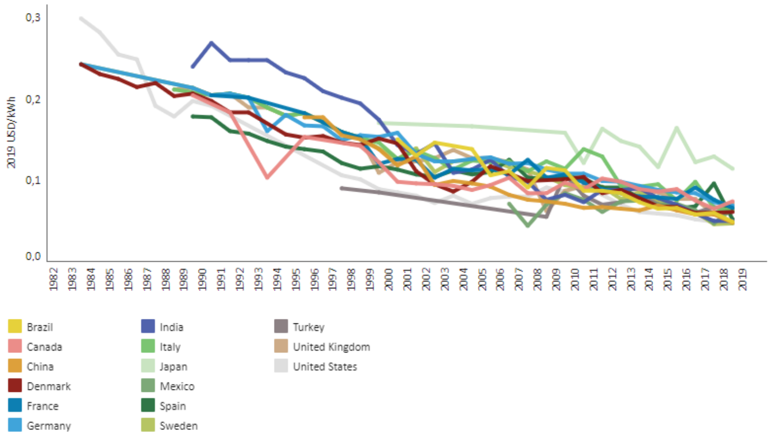

Figure 3.1: Weighted-average LCOE of Wind. IRENA.

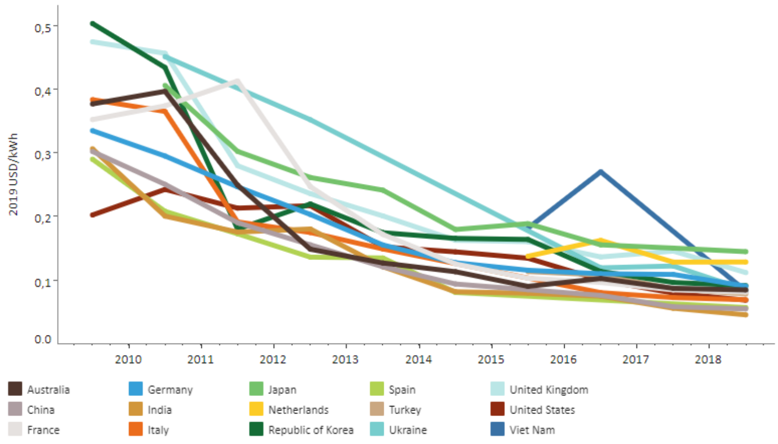

Figure 3.2: Weighted-average LCOE of Solar. IRENA.

It is worth noting that in Brazil, the capital expenditure (CAPEX) for wind energy ranges from 3,200 to 5,500 R$/installed-kW, while for solar, it ranges from 2,500 to 5,000 R$/installed-kW, according to [25].

Brazilian path

Hybrid power plants have been under study by the EPE since 2017. The EPE initially released three technical notes on the subject. The first one, published in 2017, discussed a methodology for calculating concurrent generation curtailment in wind-photovoltaic power plants [22]. The second one showed conceptual discussions on the types of combinations and commercial and regulatory aspects [14]. The third one covered international experiences and topics related to planning [21].

Subsequently, in 2019, ANEEL ("Agência Nacional de Energia Elétrica," in Portuguese) launched a Public Consultation 14/2019 [26]. This consultation sought input on the development of a specific standard for hybrid power plants, raising important questions about their technical and commercial aspects.

In December 2020, the EPE published a Technical Note [16] outlining initial considerations for calculating the Firm Energy Certificate (FEC) of wind-solar hybrid power plants. The note takes into account constraints resulting from the limitation of the NAC capacity and discusses the impact of numerous variables such as temporal discretization, concomitance of measurements, long-term effects, and interannual variability. As we will see later, FEC is a crucial variable for energy commercialization contracts and the current supply adequacy mechanism. Therefore, it is essential to establish a methodology that accurately reflects this magnitude.

In 2020, ANEEL launched Public Consulting 61/2020, which was divided into two phases and led to the publication of Resolution 954 on November 30th, 2021 [17]. This resolution established specific rules for hybrid power plants. Prior to this, the regulatory framework allowed for a NAC capacity lower than the sum of the individual sources' installed capacities within hybrid power plants. The new regulation introduced a flexible NAC capacity, where a hybrid power plant can contract between the highest source installed capacity and the total installed capacity of the plant. This regulatory innovation allows for significant NAC cost savings while incentivizing the hybridization of complementary sources that can reduce the need for network expansion.

For instance, in October 2022, the first flexibilization was granted for a solar-wind hybrid power plant, which received permission [27] to establish M within a range of 471 MW and 590 MW. This flexible NAC capacity is an important development in the regulatory framework for hybrid power plants in Brazil, as it provides more opportunities for renewable energy integration and cost savings.

It is worth noting that the hybrid generation is allowed by regulation to reduce or increase NAC annually.

Despite recent advancements in the regulatory framework for hybrid generation in Brazil, there are still some areas that require further development. For instance, an official methodology to calculate the Firm Energy Certificate (FEC) for hybrid power plants has not yet been established, which is an essential variable for trading energy contracts and the current supply adequacy mechanism. In this dissertation, we aim to address this gap and propose a methodology for calculating the FEC for hybrid power plants in Brazil.

4
Regulatory framework

Chapter 3 discussed important aspects of hybrid generation. In chapter 4, we will focus on key regulatory aspects related to Firm Energy Certificates (FECs), which are an essential component of energy commercialization contracts in Brazil. We will also highlight the gap in FEC methodology for hybrid power plants. Additionally, we examine the evolution of network-access contracts in Brazil and the issue of generation curtailment.

4.1
Firm Energy Certificate (FEC) in Brazil

The Firm Energy Certificate (FEC) is a measure of energy reliability that indicates the sustainable supply of energy, usually expressed in average MWs (avgMW). It determines the maximum amount of energy that a power plant can supply, based on a defined supply criterion, and is used as a stamp of energy reliability. About FEC in Brazil, we recommend for interested readers the references: [28], [29]. For instance, the FEC is used to determine the maximum amount of energy that a power plant can commercialize in forward contracts, denoted by Q. However, while there is an established methodology to calculate the FEC for individual power plants, there is currently no official methodology for calculating the FEC for hybrid power plants, which is a gap in the regulatory framework that needs to be addressed.

The responsibility for calculating the FEC of generation projects and their revisions lies with EPE and follows methodologies and criteria defined by specific regulations regarding generation sources, the first calculation and the revision process. This concept is intrinsically related to supply adequacy, resumed below.

For historical reasons, the current regulation uses a different methodology for each type of source. Furthermore, besides its relevance to planning studies, the FEC also has a significant impact on market decisions, as it defines the maximum regulatory amount that a generator can sell in forward contracts (see [?] for further details). Thus, the discrepancies among the FEC calculations constitute a regulatory distortion that can discriminate sources in both long-term studies, auctions, and market competitiveness. It is interesting to mention that none of the methodologies acknowledges the strong generation seasonality to which most of these sources are subject, and only wind generators have their FEC calculated based on a reliability index (low percentile).

4.1.1 Supply Adequacy in Brazil

Related to FEC, the problem of the reliability of supply encompasses two elements that can be conceptualized in terms of the provision of two public goods. On the one hand, we have short-term reliability—or “the ability of the electric system to withstand sudden disturbances”, in particular during peak hours—and on the other hand “capacity adequacy”—or “the ability of the electric system to supply the aggregated electrical demand and energy requirements of costumers at all times” — which conditions the supply of the former good according to usual definitions [30].

According to Perez et al. [31], the security of the electricity supply can be observed from four dimensions, ranging from long-term to short-term, as follows:

– Strategic expansion policy: very long-term availability of energy.

– Adequacy: refers to the existence of enough available generation and network to meet demand in the long term efficiently.

– Firmness: the ability to respond to actual requirements to meet demand efficiently.

– Security: the short-term ability of the electrical system to support unexpected disturbances.

Regulators worldwide face the challenge of ensuring a reliable supply of electricity in both the long and short-term, and Brazil is no exception. As a response to the electricity shortage of 2001, the country has adopted supply adequacy mechanisms, including the Firm Energy Certificate (FEC), which has played a crucial role. Since then, Brazilian regulators have designed various supply mechanisms. However, a persistent challenge remains the coordination of economic incentives and their adaptability to the evolving electricity landscape.

Brazil has implemented various supply adequacy mechanisms that align with the four dimensions of supply security. These mechanisms include: first (i) the long-term PPA, or forward contracts, associated with finance with government subsidies addresses the Strategic expansion policy. Regarding Adequacy, two tools have been adopted: (ii) 100% of consumption cannot surpass the FEC of generation suppliers and (iii) the reserve supply of energy above the sum of FEC of the system. Down to short-term adequacy, we have the (iv) centralized risk management applied to energetic models as Newave and Decomp and, finally, (v) the out-of-merit-order dispatch addresses Firmness and Security dimensions. For a more detailed discussion of these mechanisms, please refer to [32].

4.1.2 Centrally Dispatchable Power Plants

In Brazil, the concept of firm energy certificate (FEC) is applied to dispatchable power plants, which are units operating under the coordination of the national system operator. The FEC represents a share of the global long-term energetic supply capacity and is calculated based on dispatch simulations by the system planner(EPE – *Empresa de Pesquisa Energética*). The Ministry of Mines and Energy (MME) issues the FEC, which is used to ensure that the total energy supplied by a coordinated system with multiple hydropower plants, operating under different inflow regimes and interconnected by complex cascades, is higher than the sum of the energies that would be achievable on an individual basis. This accounts for the portfolio effect, which enhances the reliability of the system.

The current regulation [33] establishes the rules for calculating the FEC of energy from hydroelectric and thermal power plants that are centrally dispatched. The calculation process involves several steps. First, the Newave model is used to project the generation and load of the Brazilian System ("Sistema Interligado Nacional") and calculate the critical load of the system with the Newave model addressed. The features and risk aversion of the model Newave can be found in [34]. Next, the critical load of the Brazilian System is divided into hydro and thermal fractions. This division enables the allocation of the FEC among hydro and thermal power plants and ensures that each plant contributes to the overall reliability of the system.

In the case of hydroelectric power plants, the fraction of the critical load is divided among the plants based on their generation output, or "Energia Firme," as calculated by the Suishi model. This model is designed to determine the firm energy generation of hydroelectric plants and is characterized by its specific features, which are detailed in [35].

For thermal power plants that declare their operational costs (known as "Custo Variável Unitário" or CVU in Portuguese), the fraction of the critical load is distributed based on the maximum availability of each plant, as specified in the current regulation [33].

Summarizing, the allocation of the FEC for dispatchable units in Brazil is determined by calculating their share of the overall energy supply capacity of the system. For a more in-depth discussion of the methods and references related to this approach, please refer to [36].

4.1.3 Non-controllable and Renewables Power Plants

For non-controllable renewable power plants, including wind and solar sources, classified as non-dispatchable units, the FEC is issued based on quantiles of the annual average historical generation availability, as further detailed.

4.1.3.1 Wind

A certified energy company calculates the annual production of a wind power plant. Since 2013, the methodology for estimating the Firm Energy Certificate (FEC) for wind power projects in Brazil is been revised. According to EPE, the FEC for a wind power plant corresponds to the annual energy value that is exceeded with a probability of occurrence equal to or greater than 90% for the projected 20-year lifespan of the plant. This calculation takes into account the uncertainties presented by the certification company, as well as the expected unavailability, internal consumption, and electrical losses up to the point of connection to the grid. As we understand, the wind's FEC corresponds to the 10^{th} percentile of annual generation.

4.1.3.2 Solar

For solar power plants, the methodology refers to the annual energy value that is exceeded with a probability of occurrence equal to or greater than 50% for the projected 20 years. A certified energy company also calculates this methodology and considers uncertainties, expected unavailability, internal consumption, and electrical losses up to the point of connection to the grid. As we understand, the solar's FEC corresponds to the 50^{th} percentile of annual generation.

4.1.3.3 Small Hydro Plants (SHP)

The Small Hydro Plants' FEC calculation is relatively simple compared to other sources. It is based on the historical inflow of the river, and the FEC is calculated as the average production. For a more detailed explanation of the calculation method, please refer to [37].

FEC's Revision

The FEC of power plants is periodically revised according to regulation. This process depends mainly on the characteristics of the power plants, whether they are dispatchable or non-dispatchable, as we further explain.

4.1.3.4
Dispatchable Power Plants

The FEC of hydroelectric power plants is subject to review every five years, which is referred to as the ordinary review. Additionally, an extraordinary review may be triggered in the occurrence of relevant events.

The last FEC's ordinary review occurred in 2022. The purpose of this review is to adjust the FEC of all plants based on developments in the system, such as improvements in its representation, computational models, data availability, and other parameters, such as risk aversion and deficit cost.

4.1.3.5
Non-Dispatchable Power Plants

The FEC of wind power plants undergoes a revision when the annual average generation (G^W_{avg}) falls below 90% or exceeds 105% of the current FEC ($FEC_{current}$), as specified in the current regulation [38]. The updated FEC ($FEC_{revised}$) is calculated using the following formula:

$$For \qquad G^W_{avg} \leq 90\% FEC_{current} \quad or \quad G^W_{avg} \geq 105\% FECcurrent \tag{4-1}$$

$$FEC_{revised} = G^W_{avg} \tag{4-2}$$

Similarly, – despite the non-symmetric range – the FEC of *solar* power plants is subject to revision [39] when the average solar generation (G^S_{avg}) falls outside the range of ninety-five percent (95%) to one hundred and five percent (105%) of the current FEC ($FEC_{current}$), as expressed by the following formula:

$$For \qquad G^S_{avg} \leq 95\% FEC_{current} \quad or \quad G^S_{avg} \geq 105\% FECcurrent \tag{4-3}$$

$$FEC_{revised} = G^S_{avg} \tag{4-4}$$

Therefore, in spite of the differences in the calculation methods previously described, we emphasize that for non-dispatchable power plants, which include renewable sources such as wind, solar, and small hydro plants, the annual average generation should correspond to the FEC. Therefore, the FEC serves as the benchmark for Brazilian regulation in the proposed unifying FEC.

4.1.4 Hybrid generation sources

Prior to the publication of this work, there was no official methodology for calculating the FEC of hybrid power plants in Brazil. It was partially due to the challenges and incompatibilities associated with the different methodologies used to calculate the FEC of individual generation sources, as we have discussed. As a result, there was no established method for aggregating the contributions of multiple generation sources in a hybrid plant.

Remarkably, the EPE presented initial considerations for the FEC calculation of a hybrid power plant composed of wind and solar sources. The proposed methodology suggests first calculating the generation curtailment caused by the reduction of the network-access contract. This includes evaluating at least three years of verified or estimated wind generation and local anemometric measurements. For the solar unit's irradiation, a concurrent measurement history may be used if available, or the Typical Meteorological Year (TMY) can be used to estimate photovoltaic energy production for each available wind year. The calculated curtailment is then used to reduce the hybrid FEC, preferably by cutting the most recent FEC of the sources among the power plant. For instance, in an existing wind power plant further expanded with a solar power plant, with a calculated $FEC^{S}_{initial}$, because jointly with the wind plant, it is expected a curtailment of y results on $FEC^{S}_{final} = FEC^{S}_{initial} - y$. More details can be found in [16].

The proposed hybrid FECs by EPE was an important first step, but we can identify some flaws in the methodology. For instance, the use of uncorrelated wind and solar generations in the calculation may not adequately consider the complementarity of these sources.

4.2 Regulated and Free Market Environmental in Brazil

The Brazilian electricity sector is divided into two markets, the ACL (Free Contracting Environment) and the ACR (Regulated Contracting Environment). In the ACR, consumers can only purchase energy from the distributor at a fixed price. The regulated market (ACR) is composed of captive consumers, that is, those who are served by electricity distribution companies and do not have the option to choose their electricity supplier. In this market, electricity prices are set by government auctions and regulated by the National Electric Energy Agency (ANEEL).

Conversely, the free market (ACL) is composed of free and special consumers who have the option to choose their electricity supplier and negotiate electricity prices directly with generators or electricity traders. In this market, prices are freely defined according to supply and demand, and CCEE is also responsible for managing the accounting and settlement system for electricity buying and selling operations.

Historically, the ACR enabled a greater amount of new energy through long-term contracts. The ACL was more commonly used for short-term contracts, helping to bring competitiveness to the regulated market by allowing generators to negotiate their surpluses and deficits more quickly.

In recent years, the ACL has been gaining strength, as evidenced by the significant increase in consumption, from 15,685 avgMW in 2016 to 24,496 avgMW in 2022. Additionally, according to CCEE [40], the percentage of consumption in the ACL has risen from 25.5% in 2016 to 36.5% in 2022.

On the generation side, the ACL has taken the lead in expansion. The competitive advantage of renewables, as demonstrated earlier, combined with long-term contracts (PPAs), enables new power plants to sell energy exclusively to the ACL. According to a study conducted by Abraceel [41] in April 2022, 76% of the generation capacity currently under construction is destined for the ACL. This represents a significant shift in the expansion of the Brazilian energy matrix.

The study cases in this work consider long-term quantity contracts negotiated in the market to enable these new power plants, such as renewable hybrid parks. In the last study case, we compare the regulated and free markets signals of expansion applied to a hydrid power plant.

4.3 Network-access contract

The network-access contract (NAC) represents the maximum amount of energy that a generator or consumer can inject or demand from the power grid or transmission system. It is a crucial factor for ensuring the reliability and stability of the power system. The lack of an adequate NAC can result in future load losses for consumers or curtailment for generators. In the Brazilian power system, the NAC is referred to as "Montante de Uso do Sistema de Transmissão" (MUST).

Brazilian Regulation

The cost of using the Brazilian high-voltage transmission network (230+ kV), also known as the "Rede Básica", is shared by consumers and generators connected to it. In accordance with current Brazilian regulations, a minimum amount of network-access contract (NAC), denoted as M, must be equal to the total installed capacity of the power plant. This assumes that the power plant will inject its full capacity into the system in at least one 15-minute interval, as stipulated by current regulations.

Recently, a new understanding is been applied to hybrid power plants; as they combine two or more generally complementary sources, the probability of the sources achieving the maximum at the same time is very small. Therefore, the benefit of complementarity between sources composing hybrid power plants could also be captured at the network level. The current regulatory framework allows a reduced amount of network-access contract (NAC) for hybrid power plants, lower than the sum of the individual sources' installed capacities. This regulatory innovation was considered in the proposed regulation [17] regarding the flexibilization of NAC. Under this new regulation, a hybrid may contract NAC between the highest source installed capacity and the total installed capacity of the plant. This feature allows for significant NAC cost savings while incentivizing the hybridization of complementary sources, which in turn helps to relieve network expansion needs. Annually, the hybrid generation is allowed by regulation to reduce or increase NAC.

We should note that in October 2022, the first solar-wind hybrid power plant received permission to establish a flexible range for M between 471 MW and 590 MW. This is the first instance of flexibilization being applied to a hybrid power plant in Brazil. It represents a significant step towards recognizing the benefits of complementarity between sources and encouraging the adoption of hybridization in the power sector.

Nevertheless, when generation injection surpasses the network-access contract M, a penalty must be paid. According to regulation [42], generators are subject to a penalty, monthly calculated when the injection is higher than the contracted amount M plus a tolerance ϵ. For each month m, the penalty can be expressed as the maximum violation of the tolerance within all $t \in \mathcal{T}_m$.

In practical cases, however, depending on the generation technology, penalties can be prevented by curtailing generation in real-time operation.

In Brazil, the network-access contract is established through an agreement known as "Contrato de Uso do Sistema de Transmissão" (CUST). This contract stipulates the maximum amount of power that a generator or consumer can inject or demand from the power system and is valid for at least one year. It is important to note that consumers can change the value of their NAC; however, they are subject to restrictions within the next four (4) years.

The generator is typically required to seal the contract for one value of NAC for the whole period of authorization, which is usually for a period of 25 or 30 years. However, an exception was made for hybrid power plants in the 2021 regulation [17], which allows for flexibility on NAC. Under this regulation, the amount of NAC can be reduced by 5% per year without any extra charges for the generator.

Generation Curtailment

The curtailment is the deliberate reduction in output of generation below what could have been produced. The loss from curtailing generation based on renewable energy sources is generally seen as an unacceptable solution by the public. This view could lead to overinvestment in grid infrastructure and overcosts for renewable energy sources; however, some curtailment of fluctuating (variable) generation is optimal according to [43].

California has experienced a rapid increase in renewable energy capacity, particularly in solar generation. In 2022, the combined energy curtailed from solar and wind generation totaled 2,449,247 MWh. Of this, solar curtailment accounted for 6% of the available generation, while wind curtailment was nearly 1%. Compared to the previous year, the 2022 curtailment represents a significant increase of 62%.

Similarly, Brazil is also experiencing an increase in curtailment due to the expansion of non-controllable renewables as its energy matrix undergoes a transformation from a predominantly hydro-based fleet with thermal backup sources to a more diversified renewable energy mix that requires greater flexibility. This shift in the energy mix highlights the need for Brazil to invest in modernizing its grid infrastructure and grid management systems to ensure efficient utilization of renewable energy sources and minimize curtailment rates.

In this work, we focus on the curtailment caused by the lack of NAC constraining the available generation output, exactly the variable that the generator can select in optimizing hybrid power plants according to Brazilian regulations.

This study focus on curtailment resulting from a lack of network-access contract (NAC) that limits available generation output. This variable is precisely what generators can manipulate when optimizing hybrid power plants in compliance with Brazilian regulations. By examining the impact of NACs on curtailment regarding the framework of Chapter 6, we aim to increase the economic efficiency of renewable energy generation in Brazil.

5
The Proposed Unified FEC for Renewables and Hybrid Units

It is worth mentioning that the first objective of this paperwork as stated in Chapter 1 is to define a non-discriminatory FEC calculation methodology for hybrid power plants in Brazil.

Chapter 4 showed that certification companies calculate the historical variables and other parameters according to each technology for non-controllable renewables, which corresponds for wind units to the 10^{th} percentile of the annual average generation and for solar units, the 50^{th} percentile.

Interestingly, and in addition to the previous differences between sources, different revision procedures are used for each type of source. Therefore, although the regulation aims at assigning and revising FEC of non-controllable renewables that are intrinsically associated with their expected annual generation capacity, for historical reasons, the current regulation uses a different methodology for each type of source. As the FEC constitutes a relevant regulatory index with a significant impact on market decisions as it is the maximum amount that units can sell in forward contracts; this discrepancy constitutes a regulatory distortion that can discriminate sources in both long-term studies, auctions, and market competitiveness. Moreover, none of the methodologies acknowledges the intrinsical and strong generation seasonality to which most of these sources are subject, and only wind generators have their FEC calculated based on a reliability index (low percentile).

In addition to the above regulatory incompatibilities, the recent interest in hybrid power plants has triggered further issues on the subject. First, how to calculate a single FEC for a hybrid power plant composed of two different sources, e.g., wind and solar, each of which with its own FEC calculation methodology? Second, due to the high complementarity between wind and solar sources, the NAC amount, M, of the hybrid power plant can be, generally, reduced to a value lower than the sum of the installed capacity of the two sources. This can reduce NAC payments and network expansion costs without significantly compromising the revenue of the hybrid plant, as will be further demonstrated. However, in case of reducing the NAC amount, the generator would curtail the exceeding generation, forgoing some potential revenue from the spot market, to avoid heavy penalty charges for violating the

NAC. This introduces a second layer of complexity, as the FEC calculation would be affected by a reduced (truncated on the NAC amount) generation of the hybrid power plant. *Hence, the coherence between the main transmission and generation expansion indexes (NAC and FEC) with a non-discriminatory regulatory contracting limit for non-controllable renewables and hybrid power plants relies on a unified FEC calculation methodology for these sources.*

Accordingly, we propose in this chapter a unified FEC for non-controllable sources that can coherently accommodate 1) the hybridization of different sources, 2) capture the complementarity synergy among them, and 3) consider the effect of NAC. For didactic purposes, hereinafter, we will consider only the case of two sources, wind and solar. Notwithstanding, the whole developments and proofs in the sequel can be easily extended to the case of more than two generic non-controllable sources.

5.1 The unified truncated expected-value-based FEC (TEV-FEC) for renewables and hybrid power plants

Taking into consideration the parsimony principle, in this section, we will present the simplest version of our proposal, the *truncated expected-value-based FEC* (TEV-FEC), which constitutes the minimal change in the current regulation needed to make a coherent unified and non-discriminatory framework for renewables.

It is important to highlight that if the aim of FECs in the current regulation relies on energetic contributions, expectations (or averages) play a better role in quantifying the integral of the energy supplied within a given period than quantile.

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

$$\mathbb{F}(\mathbf{G}, M) = \frac{1}{|\mathcal{H}|} \sum_{t \in \mathcal{H}} \min\{G_t, M\}. \tag{5-1}$$

Function (5-1) is concave on M and $\mathbf{G}$ as it is a weighted sum of the minimum between linear functions. Figure 5.1 illustrates this function on the M dimension.

Based on the general definition of the TEV-FEC, provided in (5-1), we can define the FEC of a hybrid power plant with 1 MW of total installed capacity, composed of a x-MW solar generator and a $(1-x)$-MW wind

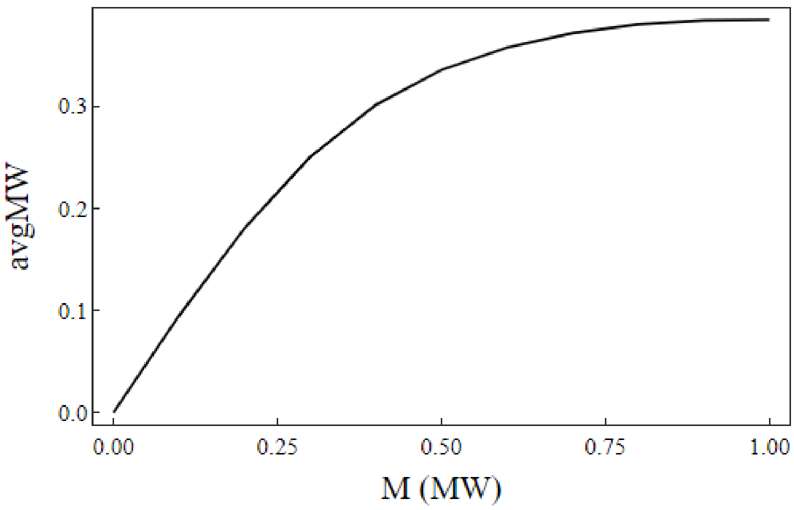

Figure 5.1: FEC as a function of NAC amount M.

generator, as $\mathbb{F}(\mathbf{G}^H(x), M)$, where $\mathbf{G}^H(x)$ is defined as follows:

$$\mathbf{G}^H(x) = x\mathbf{G}^S + (1-x)\mathbf{G}^W. \tag{5-2}$$

Thus, the TEV-FEC of non-hybrid units rests on the specific cases of $x = 0$ and $x = 1$. Note that in (5-2), we need to consider paired historical generation for the wind and solar sources, i.e., $G_t^H(x) = xG_t^S + (1-x)G_t^W$ for $t \in \mathcal{H}$, and that both wind and solar generation vectors consider normalized generation availability in percentages of their maximum installed capacity to meet the one-MW definition above. Based on (5-1) and (5-2), we can state the following theorem:

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

$$\mathbb{F}(\mathbf{G}^H(x), M) \geq \mathbb{F}(x\mathbf{G}^S, xM) + \mathbb{F}((1-x)\mathbf{G}^W, (1-x)M). \tag{5-3}$$

Proof: As we know that the minimum between two linear functions is a concave function [44], the following inequality holds $\forall t \in \mathcal{H}$ and $x \in [0,1]$:

$$\begin{aligned} \min\{xG_t^S + (1-x)G_t^W, xM + (1-x)M\} \geq \\ x\min\{G_t^S, M\} + (1-x)\min\{G_t^W, M\} = \\ \min\{xG_t^S, xM\} + \min\{(1-x)G_t^W, (1-x)M\}. \end{aligned} \tag{5-4}$$

By averaging the first and the last term of (5-4) we have:

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

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

$$\begin{aligned} \mathbb{F}(xG_t^S + (1-x)G_t^W, M) \geq \\ \mathbb{F}(xG_t^S, xM) + \mathbb{F}((1-x)G_t^W, (1-x)M).\blacksquare \end{aligned} \tag{5-6}$$

Remark 1: ***Theorem 1*** *tells us that there is a potential gain of synergy in terms of FEC associated with hybrid units, which constitutes an additional incentive for hybridization. We will further see in our empirical studies that this gain, for a hybrid power plant with $x \in (0,1)$, is maximum on values of NAC lower than the sum of the total installed capacities, i.e., $M < 1$. This provides evidence that the proposed TEV-FEC connects the incentives for hybridization with the benefit of transmission expansion cost savings.*

Finally, it is relevant to mention that due to the TEV-FEC is based on the expected value of an annual average, intervals typically considered in annual revision processes can be based on the critical intervals of a hypothesis test for the mean. In subsection 5.3 we describe this proposition.

5.1.1
Empirical studies

The key aspect behind the inequality (and possible gain) in **Theorem 1** is the fact that the combination of two complementary sources may reduce the risk of curtailments, which happen whenever $xG_t^S + (1-x)G_t^W > M$. It is easy to see this fact, as the cap (truncation) on M is the only part that, if removed, would turn (5-3) into equality, which is due to the linearity property of the expected value operator. To empirically quantify this gain, we can define it as the difference between the TEV-FEC for the hybrid power plant and the sum of the TEV-FEC for the individual sources composing it, i.e.,

$$\begin{aligned} gain(x, M) &= \mathbb{F}(\mathbf{G}^H(x), M) \\ &-[\mathbb{F}(x\mathbf{G}_t^S, xM) + \mathbb{F}((1-x)\mathbf{G}_t^W, (1-x)M)] \end{aligned} \tag{5-7}$$

We are here taking into consideration the hybrid power plant composed of solar and wind sources with a total installed capacity of 1 MW. To illustrate the gain for different values of M, we arbitrarily select $x = 0.5$ (hybrid half wind/solar) and plot the $gain(0.5, M)$ in Figure 5.2. Remind that when $M < 1$, generation may be curtailed and not count for the FEC of the power plant, this effect is more often in individual sources than in the hybrid unit that shares the M among them. The summation of wind (green line) and solar (yellow line) is represented by the segmented black line, while the hybrid is the continuous black line. The gap between these two black lines represents the gain of a hybrid power plant in terms of FEC, which is highlighted in the bar graph below. It must be noted that the $gain$ is zero at the borders of M, especially important where the network-access contract amount reaches the total installed capacity. Bellow that, particularly in the range $M \in [0.3, 0.6]$ we see a considerable gain of hybrid plants in terms of FEC.

Additionally, applying the same calculus in Figure 5.3, for x's ranging from 0.0 to 1.0 it is possible to see the highest gain of hybrid behavior according to different share of sources. We observe that the maximum $gain$ happens for a particular M which depends on each x.

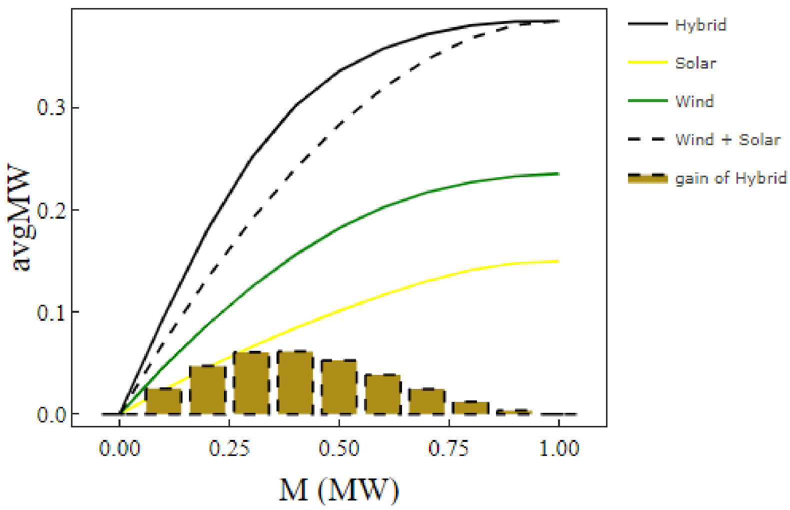

Figure 5.2: FEC Comparison of Hybrid and spitted sources for $x = 0.5$.

The relationship between higher revenue and higher M is not direct. The definition of M should consider three non-trivial relations: 1) the higher

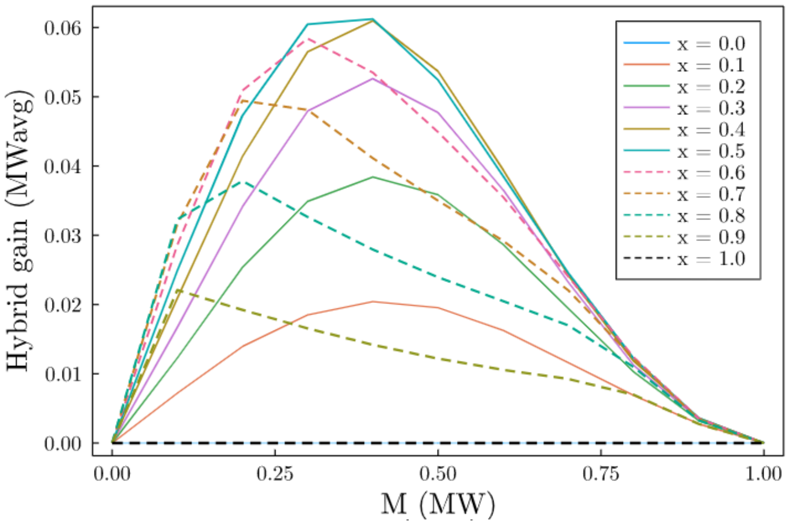

Figure 5.3: Hybrid's gain in FEC compared to separated sources, according to x.

the value of M, the greater the value of FEC is, thereby the greater one can sell in forward contracts; 2) the complementarity gain in terms of FEC for the hybrid power plant intrinsically and non-trivially depends on M and x; 3) the higher the M, the greater are the costs of transmission. Then, in the next Section, the interaction between M, x, and the risk-adjusted revenue of a hybrid power plant is characterized through a coherent risk measure and the optimal joint contracting strategy and is defined by a two-stage stochastic optimization model.

5.2 Seasonal TEV-FEC | Auxiliary proposition

In addition to the last section, we provide extensions for the proposed TEV-FEC, $\mathbb{F}_m(\mathbf{G}^H(x), M)$, for a hybrid power plant considering other interesting aspects, also left behind in the current regulatory framework, such as seasonality and reliability.

The seasonality extension is straightforward. We just need to consider interannual, such as monthly or quarterly, calculations of (5-1). For didactic purposes, hereinafter, we use a monthly discretization. Thus, for each month $m \in \{1, ..., 12\}$, one just needs to filter from the complete historical data $\mathcal{H}$ used to calculate (5-2), the generation associated with hours in month m, i.e., $\mathcal{H}_m$, as follows:

$$\mathbb{F}_m(\mathbf{G}^H(x), M) = \frac{1}{|\mathcal{H}_m|} \sum_{t \in \mathcal{H}_m} \min\{G_t^H(x), M\}. \tag{5-8}$$

It is easy to see that **Theorem 1** is valid for (5-8), as it has the same structure, but considering a subset of data in the summation in comparison to (5-1). Although the optimal contracting strategy based on extensions of the TEV-FEC was not covered in this paper, the model (6-5)–(6-11) can be easily extended to consider any concave FEC as (5-8). The consideration of a seasonal FEC, notwithstanding, may trigger further discussions on more sophisticated seasonal or multistage trading strategies. This is left as an interesting topic for future research.

5.3 Revision of FEC

As we conclude in Chapter 4.1.3.5 the FEC revised corresponds to the annual average generation (mean). Therefore, we should analyze the preferred range of verified generation to accept or reject the FEC, i.e., revising the FEC of the power plant when the verified generation does not fit in the range.

According to the reference statistical [45] we can establish the following hypotheses, in the first the FEC is adequate and in the second it needs to be revised:

$$\mathcal{H}_0 : \frac{1}{|\mathcal{H}|} \sum_{t \in \mathcal{H}} \hat{G}_t^H = FEC_{current} \quad (5\text{-}9)$$

$$\mathcal{H}_1 : \frac{1}{|\mathcal{H}|} \sum_{t \in \mathcal{H}} \hat{G}_t^H \neq FEC_{current} \quad (5\text{-}10)$$

To do this, we will take a sample (size $\mathcal{H}$) where the average burn rate of this sample will be evaluated. Remember that the sample mean is an estimate of the population mean.

If the sample (verified generation) mean is close to the population mean (taken as FEC), we can assume that FEC is the true population mean ($\mathcal{H}_0$), and if it is a value very different from this, we could assume that is valid, $\mathcal{H}_1$. So, in this case, the sample mean is the test statistic.

In the decision-making process, as established above, given some criteria, we may obviously be making some errors. We will call these errors type I and type II errors: error Type 1 rejects the null hypothesis $\mathcal{H}_0$ when it is true; error Type 2 not rejects the null hypothesis $\mathcal{H}_0$ when it is false.

Therefore, a typical error type I and II analysis can be used to define the significance level of the test and define revision intervals that are tailored made for each power plant.

6
Co-Optimization of Network-Access and Forward Contracts

The second objective of this study, as outlined in Chapter 1, is to propose a co-optimization model that defines the optimal forward and network-access contracting strategies for a renewable, risk-averse hybrid power plant.

In Chapter 6 we present the revenue and cost structure from the generator's perspective, as well as a risk profile framework that is consistent with investment goals. Additionally, we introduce in this chapter an optimization model for network-access and forward contracts (Q) that considers the assumptions presented earlier, including the TEV-FEC discussed in Chapter 5. By offering a comprehensive approach that accounts for both revenue and risk considerations, the proposed co-optimization model can help generators to make more informed decisions about their contracting strategies and ultimately increase the profitability and sustainability of their renewable power plants.

6.1
Generators revenue and costs

The generator's net revenue can be expressed as the difference between the revenue (6-1) and costs (6-2). So, the net revenue is a function of the network-access contract (M), forward contract Q, and share of solar x. The annual revenue $\tilde{R}$, which is a random variable, comprises the contract income plus the revenue in the spot market regarding the differences between the generation and the contract as follows:

$$\tilde{R}(Q, M, x) = \sum_{t \in \mathcal{T}} [pQ + (\hat{\tilde{g}}_t^H(M, x) - Q)\tilde{\pi}_t]. \tag{6-1}$$

The cost is a deterministic function of the NAC amount and the proportion of renewable energy sources multiplied by their annualized capital expenditures (CAPEX) C^S and C^W. It is represented as follows:

$$C(M, x) = \sum_{m \in \mathcal{M}} Mc_m + xC^S + (1 - x)C^W. \tag{6-2}$$

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

6.2
Risk profile

To assess the value of random variables, in this dissertation, we make use of a coherent risk measure, namely, the conditional value at risk, to generate a certainty equivalent as per [46]. In order to do that, let us consider a risk profile characterized by a certainty equivalent (ρ) based on the Conditional Value at Risk (CVaR). So, in this setting, given a random revenue $\tilde{R}$, the certainty equivalent is defined as follows:

$$\rho_{\alpha,\lambda}(\tilde{R}) = \lambda CVaR_{\alpha}(\tilde{R}) + (1-\lambda)E(\tilde{R}). \tag{6-3}$$

This certainty equivalent metric can be recast as a linear optimization problem by means of a linear programming representation for the CVaR in $\rho_{\alpha,\lambda}$ according to expressions (7) and (8) in [47], firstly proposed in [47]. For a discrete distribution of $\tilde{R}$, with scenarios and probabilities given by $\{(R_\omega, 1/|\Omega|)\}_{\omega\in\Omega}$, $\rho_{\alpha,\lambda}$ can be represented as follows:

$$\rho_{\alpha,\lambda}(\tilde{R}) = \qquad \lambda \max_{z} \left\{ z - \sum_{\omega\in\Omega} \frac{(z-R_\omega)|^+}{(1-\alpha)|\Omega|} \right\} + (1-\lambda)\frac{1}{|\Omega|}\sum_{\omega\in\Omega} R_\omega. \tag{6-4}$$

The above formulation is suitable for linear programming problems as widely used in the related literature (e.g., see [9] and [12]).

6.3
Co-optimization model

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

$$\max_{M,Q,x,\hat{g}^H_{t,\omega},\hat{G}^H_t} \quad \rho_{\alpha,\lambda}\Big(\sum_{t\in\mathcal{T}}[pQ+(\hat{g}^H_t - Q)\tilde{\pi}_t]\Big) - \sum_{m\in\mathcal{M}} Mc_m - xC^S - (1-x)C^W \tag{6-5}$$

s.t.:

$$\hat{g}^H_{t,\omega} \leq M \qquad \forall\, t\in\mathcal{T}, \omega\in\Omega \tag{6-6}$$

$$\hat{g}^H_{t,\omega} \leq (1-x)g^W_{t,\omega} + xg^S_{t,\omega} \qquad \forall\, t\in\mathcal{T}, \omega\in\Omega \tag{6-7}$$

$$\hat{G}^H_t \leq M \qquad \forall\, t\in\mathcal{H} \tag{6-8}$$

$$\hat{G}^H_t \leq (1-x)G^W_t + xG^S_t \qquad \forall\, t\in\mathcal{H} \tag{6-9}$$

$$Q \leq \frac{1}{|\mathcal{H}|}\sum_{t\in\mathcal{H}} \hat{G}^H_t \tag{6-10}$$

$$M, Q, \hat{g}^H_{t,\omega}, \hat{G}^H_t \geq 0, \text{and } x\in[0,1] \tag{6-11}$$

In (6-5)–(6-11), the objective function comprises the maximization of the CVaR-based certainty equivalent, (6-3), applied to the net revenue, i.e., the difference between expression (6-1) and (6-2). As costs are deterministic, and the $\rho_{\alpha,\lambda}$ is shift additive (see [46]), the cost can be considered out of the certainty equivalent. Additionally, by considering $\hat{g}^H_{t,\omega}$ as a variable decision, expressions (6-6) and (6-7), impose that this variable lies in the hypograph of the hybrid power plant truncated generation, i.e., that $\hat{g}^H_{t,\omega} \leq \min\{(1-x)g^W_{t,\omega} + xg^S_{t,\omega}, M\}$. Actually, as 1) $\hat{g}^H_{t,\omega}$ is multiplied by positive coefficients (as spot prices are positive, i.e., $\tilde{\pi}_t \geq 0$) and 2) $\rho_{\alpha,\lambda}$, for $\lambda > 0$, is a non-decreasing function (see [46]), the optimal solution will always be attained on the equality, i.e., $\hat{g}^{H*}_{t,\omega} = \min\{(1-x)g^W_{t,\omega} + xg^S_{t,\omega}, M\}$. The same rationale applies to $\hat{G}^H_t$ and expressions (6-8) and (6-9). Finally, expression (6-10) defines the regulatory limit for the forward involvement based on the FEC, and (6-11) defines the limits of each variable. Model (6-5)–(6-11) can be recast as a linear optimization problem by replacing $\rho_{\alpha,\lambda}$ in (6-5), with its linear counterpart (6-4). On behalf of brevity and to avoid redundancy, we omit this reformulation.

6.4 Dynamic revision process for the FEC

Remind that the TEV-FEC considers historic generation truncated by M. Considered by equation (6-10), the algorithm automatically refreshes the FEC of the power plant according to the generation $\hat{G}^H_t$ and selected M. Therefore, we conclude that the revision of FEC is intrinsically included in our model.

7
Case Studies

In Chapter 6, we have developed a comprehensive methodology to optimize the network-access contract (M), the forward contract (Q), and the source participation (x) for hybrid power plants. This approach is intended to benefit investors in the generation sector, regulators, and planners alike, by providing a robust and flexible framework to support decision-making.

This Chapter 7 will feature a series of case studies, each of which is designed to illustrate a key feature of the proposed methodology.

- The first study involves testing the co-optimization of forward and network-access contracts for a hybrid power plant comprising 50% wind and 50% solar energy sources. For this study, we will use model equations (6-5)–(6-11), disregarding the CAPEX parcel in the objective function, and incorporating an additional constraint that enforces $x = 0.5$.
- In the second study, we will conduct sensitivity analyses on the shares (x) to assess their effect on the optimal contracting strategies. Specifically, we will examine the optimal responses $M^*(x)$ and $Q^*(x)$, utilizing the same constrained model from the first study but varying the constraint on x for different values.
- The third study will focus on co-optimizing x with M and Q, examining the optimal solution as a function of the annualized CAPEX of two sources composing the hybrid power plant. This approach considers the complete objective function (6-5), providing a comprehensive assessment of the optimal strategy.
- The fourth study aims to analyze and compare the most effective contracting strategies for M, Q, and x (source participation) in both quantity or availability contracts. By identifying the underlying causes and consequences of these strategies, we can gain insight into their potential impact on the expansion of the energy matrix.
- The fifty study aims to analyze the risk-aversion preferences and, consequently, the hybrid power plant optimized by the model.

Through these case studies, we aim to provide insights into the benefits and limitations of the proposed methodology, as well as to demonstrate its practical applications in real-world contexts.

The model is implemented in Julia Language (JuMP) and solved by Gurobi. The data set used in this paper is available at [48]. We used a Notebook Intel(R) Core(TM) i7-8565U with 4 cores (1.99 GHz each) and 8 GB of RAM.

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

In this first case study, we assume a hybrid power plant half solar, half wind, i.e., $x = 0.5$. First, we assume a neutral forward market with a forward price p equal to the expected value of the average annual spot price, i.e., 83 R$/MWh, a constant network-access tariff $c_m = 7$ R$/kW/month, representing a typical cost in the Northeast of Brazil, and null CAPEX, $C^W = C^S = 0$. Regarding risk aversion, we considered $\alpha = 0.95$ and $\lambda = 0.95$. The effect of different forward prices and risk aversion will be further studied.

First, we showcase the relevance of optimizing both forward and network-access contracts. To do that, we benchmark the results of our model with the base case, compatible with the current regulatory framework, where the network-access contract should be equal to the total installed capacity. Thus, the benchmark model also comprises another constraint, i.e., $M = 1.0$.

For the benchmark, we find $Q^* = 0.3294$ and an objective value equal to $150,796$\$. Then, by co-optimizing both variables (M and Q), we find $M^* = 0.5548$ (44.52% lower than the benchmark), $Q = 0.3177$ (3.57% lower than the optimal forward contracting level in the benchmark) and an objective value of $178,159$\$ (18.15% higher than that obtained in the benchmark). In other words, the co-optimization significantly reduces the network-access contracting amount to a value that is only 10.96% higher than the installed capacity of each source (recall that in this case study, each source has 0.5 of the total installed capacity). On the forward contracting side, it is worth mentioning that the new joint contracting strategy, which is responsible for reducing 44.52% of the network-access annual costs, is made without changing too much the forward involvement strategy (only 3.57% of reduction in comparison to the benchmark). Hence, the significant improvement in the risk-adjusted revenue metric is mostly related to the reduction of network-access expenditures. Notwithstanding, the 3.57% adjustment in the forward market is necessary to compensate for the price and quantity risk due to the reduction in the generation profile.

For instance, by keeping the forward involvement equal to the benchmark, i.e., also making $Q^* = 0.3294$ and optimizing only M, the optimal solution would be $M^* = 0.5756$, and the certainty equivalent would be equal to $176,985\$$ (0.66% lower than the co-optimized strategy, yet still 17.37% higher than the benchmark). Therefore, it is clear that the co-optimization of both variables provides a significant improvement in the overall objective function.

Curtailment
It is worth mentioning that, in contrast to the significant reduction in the NAC amount of 0.5548 MW and related fixed cost savings (44.52%), the expected energy curtailment implemented to avoid exceeding the reduced NAC amount M^* is only 7.63% of the total expected value of the available generation of the hybrid power plant (with an expected frequency of 18.12% of the hours in the year). In terms of expected revenue in the spot market, this curtailed energy represents only 6.28% of the total expected revenue of the co-optimized case.

To further analyze the co-optimized strategy, we can vary the forward contract price to simulate different market conditions. To do that, we run the model (6-5)–(6-11) with $p = p_0\beta$, where $p_0 = 83$ R\$/MWh (neutral market) and $\beta \in \{0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0\}$. In Figure 7.1, we can see that the network-access contract M^* and the forward contract Q^* increase, especially the first, as the contract price grows, which is somewhat expected. However, it is interesting to see that the NAC grows faster than forward involvement, whereas M^* does not surpass 0.8102 and Q^* does not surpass 0.3805. This brings relevant evidence that hybrid power plants should be allowed to reduce their NAC amount. Additionally, the benefits of this reduction are intrinsically linked to the forward contracting strategy, thereby requiring a regulatory framework that acknowledges this link on both the FEC and NAC payments.

Case Study 2: Sensitivity on the share of solar and wind

In this subsection, we study the sensitivity of the share of sources (x) in the hybrid power plant. Thus, in this investigation, we run the same two models from the previous subsection, namely, the benchmark, where only the Q is optimized and $M = 1$, and the co-optimized model, where both Q and M are jointly optimized, for different values of x. Figure 7.2 shows results for different values of x from 0.0 to 1.0. Note that the forward contract Q is lower in the co-optimization case. As expected, co-optimizing M and Q increases

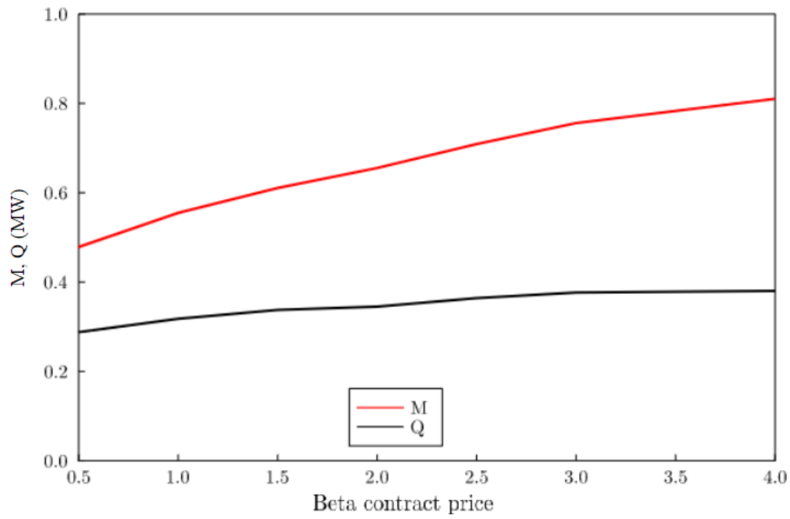

Figure 7.1: Network-access contract and Forward Contract Q according to β contract price.

the objective value. However, it is worth highlighting that, according to Figure 7.3, the gain in terms of certainty equivalent (difference between the objective function in the two cases – red and blue lines), is higher for intermediate values of x, i.e., hybrid plants benefit more from co-optimizing the NAC when developing their contracting strategy. The reason for that becomes clear in Figure 7.4, where the optimal co-optimized NAC amount M^* is depicted in red. Note that the value of M^* exhibits lower values in the intermediate values of x (with a minimum for a hybrid power plant with $x = 0.46$), where the interpretations and insights discussed in the previous section for $x = 0.5$ also apply. Notwithstanding, the boundary cases of single units, i.e., $x = 0$ (pure wind) and $x = 1$ (pure solar), also exhibit non-negligible gains and optimal contracting strategies with $M^* < 1$.

The reader may find it strange that $x = 0$ (pure wind) shows a higher objective function in Figure 7.3. However, that is true only when both sources have the same CAPEX, and this happens because the installed capacity of wind is higher than solar for the analyzed case.

Case Study 3: Sensitivity on the CAPEX of solar and wind

From Figure 7.3, the best configuration when ignoring CAPEX costs (recall that all the previously reported results neglect this term) is $x = 0$; in other words, the higher capacity factor (generation per unit of installed capacity) of the wind power producer selected in this study makes this source the most economical. However, a more comprehensive analysis should account for the annual CAPEX of the different sources composing the hybrid power

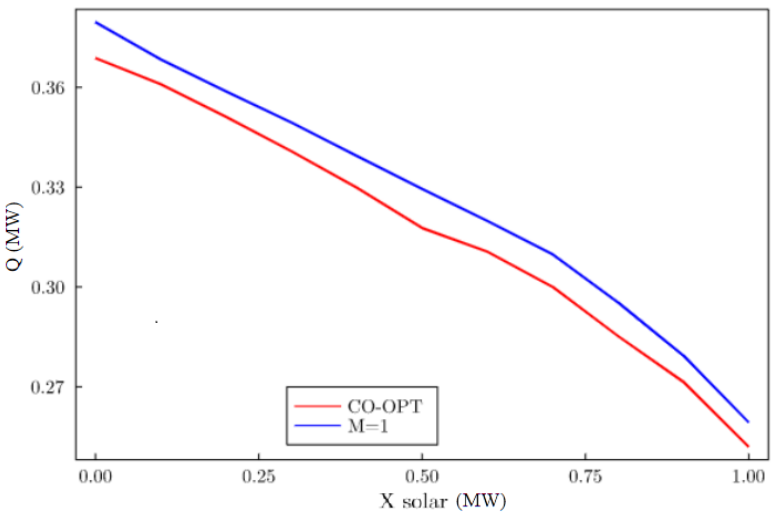

Figure 7.2: Forward Contract Q comparison co-optimization and maximum M, according to x.

plant. To study the optimal joint contracting strategy and the optimal share of the hybrid power plant, in this subsection we run model (6-5)–(6-11) with all its term and no additional constraints to define the optimal vector $[M^*, Q^*, x^*]$.

As all previously reported studies are related to the case where $C^S = C^W$, and as we know that for this case, the best solution is $x = 0$, here we run our model for different combinations of $C^S < C^W$. To facilitate this sensitivity, we parameterize $C^S = \gamma \cdot C^W$. As per [25], in Brazil, the CAPEX for wind energy ranges from 3,200 to 5,500 R$/installed-kW while solar ranges from 2,500 to 5,000 R$/installed-kW. So, we arbitrarily select $C^W = 4,000$ R$/installed-kW within the range for wind power and run a sensitivity analysis on $\gamma = \frac{C^S}{C^W} \in [0, 1]$.

The consideration of CAPEX shows a clear advantage of source combination. Figure 7.5 depicts the co-optimized strategy $[M^*, Q^*, x^*]$ for each value of γ. It is clear that for reasonable values of , e.g., $\gamma = 0.8$ ($C^W = 4,000$ and $C^S = 3,200$), hybridization becomes the best option. For instance, for $\gamma = 0.8$, the best strategy is $[M^* = 0.5968, Q^* = 0.3367, x^* = 0.3388]$. The maximum NAC reduction is obtained with $\gamma = 0.5$ ($C^W = 4,000$ and $C^S = 2,000$), which, although out of the range of CAPEX for solar units, would produce an optimal co-optimized strategy with $[M^* = 0.5410, Q^* = 0.3210, x^* = 0.4589]$.

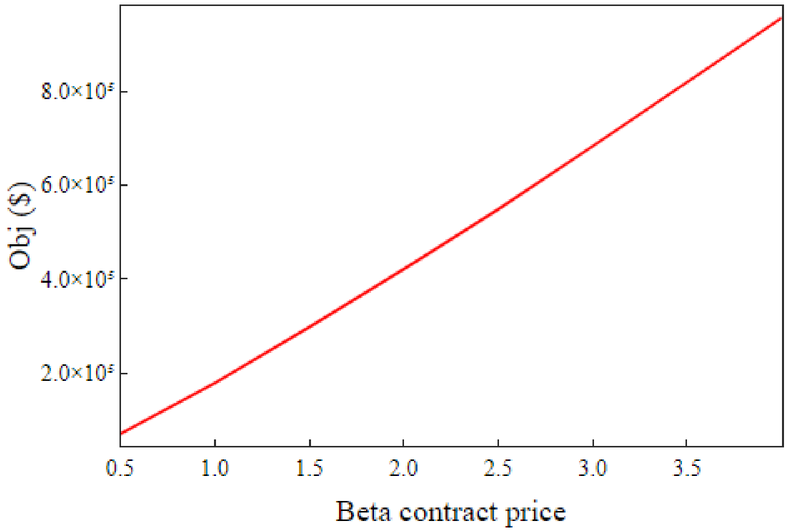

Figure 7.3: Objective value comparison co-optimization and maximum M, according to x.

Curtailment

It is worth mentioning that the NAC amount of 0.5968 MW, related fixed cost savings (41.32%), has expected energy curtailment is only 5.78% of the total expected value of the available generation of the hybrid power plant (with an expected frequency of 15.16% of the hours in the year). In terms of expected revenue in the spot market, this curtailed energy represents only 4.37% of the total expected revenue of the co-optimized case.

Case Study 4: Expansion with Quantity or Availability Contracts

In Chapter 4, we introduced the regulated and free markets in Brazil, highlighting the growing importance of the free market in the expansion of the Brazilian energy matrix. For this reason, the previous case study focused on the free market structured with a quantity contract. Furthermore, this study aims to analyze and compare the expansion signals of quantity or availability contracts.

For the didactic proposal, we distinguish the availability contract and forward contract as follows. In *availability contract*, the generator is responsible for maintaining the power plant working properly. Regardless of the verified sun or wind, the generator's outcome depends on the FEC defined previously. In this case, the counterpart of this contract (usually consumers), pays a fixed price and receives the verified generation that depends on weather conditions. In other words, the risk of sun or wind belongs to the counterpart. This is a

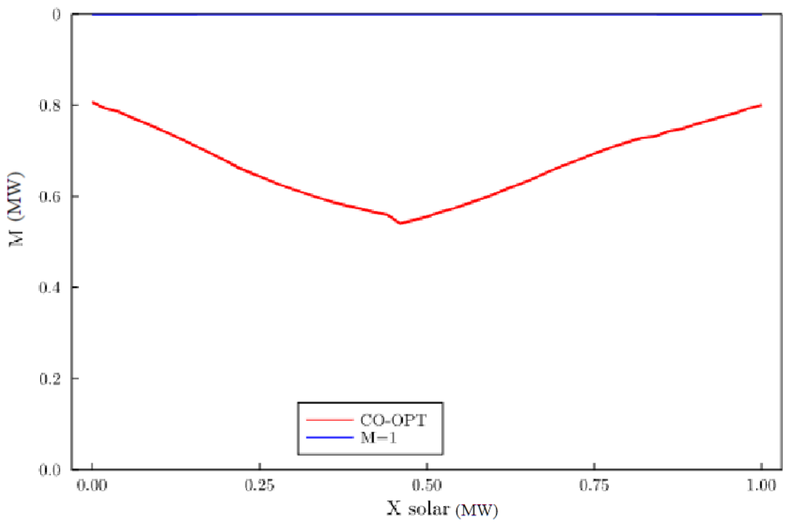

Figure 7.4: Optimum values of M according solar particition x.

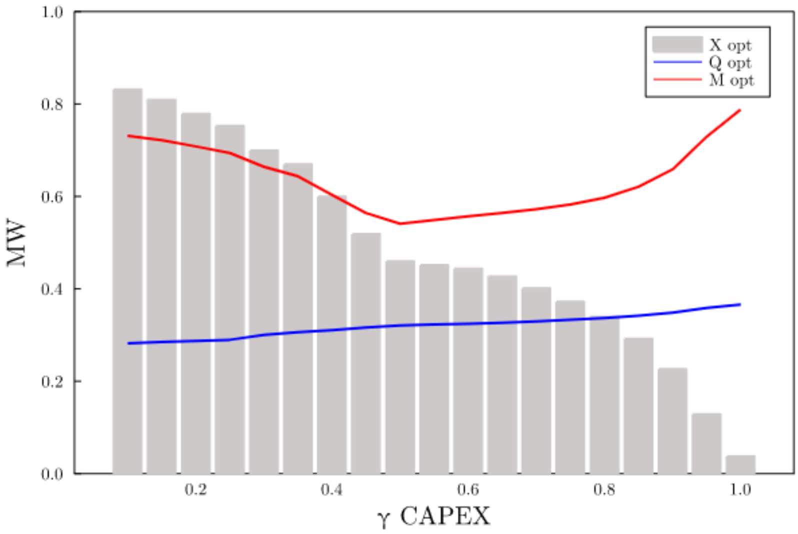

Figure 7.5: Optimum x solar, M and Q according to CAPEX defined by γ.

typical contract, defined here, of the regulated market.

On the other hand, as considered in previous cases, in *forward contract* (Q) the generator is responsible for delivering energy at the amount of Q within his resources of generation or purchasing in the spot market, thus when $\tilde{g}_t < Q$ the lack of energy is bought ($\tilde{\pi}_t$) or when $\tilde{g}_t > Q$ the excess of energy is equally sold in the spot market. This is a typical contract, defined here, of the free market.

Remind that equations (6-5)–(6-11) define the quantity market case; then, we just need to define an algorithm for the available contract regarding the regulated market. Thus, assuming the revenue of selling energy contract, with a price p, depends exclusively on FEC and the transmission costs depend on M, thus, in order to maximize the results of a generator, we present the equations (7-1)–(7-5) for the availability contract.

$$\max_{M,Q,x,\hat{G}_t^H} \quad 8760pQ - \sum_{m\in\mathcal{M}} Mc_m - xC^S - (1-x)C^W \tag{7-1}$$

s.t.:

$$\hat{G}_t^H \leq M \qquad \forall\, t \in \mathcal{H} \tag{7-2}$$

$$\hat{G}_t^H \leq (1-x)G_t^W + xG_t^S \qquad \forall\, t \in \mathcal{H} \tag{7-3}$$

$$Q \leq \frac{1}{|\mathcal{H}|}\sum_{t\in\mathcal{H}} \hat{G}_t^H \tag{7-4}$$

$$M, Q, \hat{G}_t^H \geq 0, \text{and } x \in [0,1] \tag{7-5}$$

Observe that, in this case, the entire market risk of generation is not allocated to the generator but to the counterpart of the availability contract. For that reason, the risk profile described in section 6.2 is not applicable.

In this section, we will continue assuming $\gamma = 0.8$ ($C^W = 4,000$ and $C^S = 3,200$) as in the previous section. In a free market scenario, we obtain the same results as before, i.e., $[M^* = 0.5968, Q^* = 0.3367, x^* = 0.3388]$. However, in an availability contract scenario, the results differ significantly, with M^* increasing from 0.5998 to 0.7836, indicating a substantial shift in network-access, while the solar participation x^* reduces to 0.0. It's worth noting that this reduction in solar participation is due to the lack of incentives for the generation of the power plant, which is only encouraged for the FEC calculation.

To further explore the impact of other γ CAPEX values, we have depicted the results for the availability contract scenario in Figure 7.6. When compared to the results obtained for the free market scenario in Figure 7.5, we observe that hybrid power plants are considerably less incentivized in the availability contracts scenario.

Noteworthy, the difference between optimal source participation and network-access, is a consequence of complexities and responsibility added to the generator deciding the appropriate investment to maximize its revenue. From this perspective, we see how matrix evolution can be related to the mode of expansion, whether quantity or availability contracts. The last, in which more complexities reach the decision of expansion, tends to achieve a more cost-reflexive matrix, ultimately more efficient.

In other words, the quantity contract scenario presents more challenges and uncertainties for power plants, which in turn encourages them to make more cost-conscious decisions in order to remain competitive. This tends to

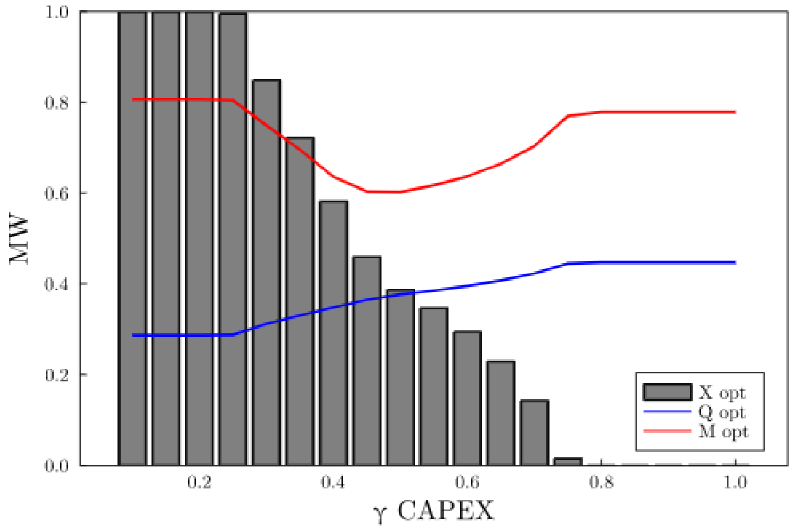

Figure 7.6: Availability contracts, optimum x solar, M and Q according to CAPEX defined by γ.

result in a more efficient allocation of resources and, ultimately, a better outcome for both the generators and the market as a whole.

Case Study 5: Risk Aversion

Remind that in our previous case studies, we used risk-aversion parameters of $\alpha = 0.95$ and $\lambda = 0.95$. In this study, we test λ from 0 (risk-neutral) to 1 (high-risk aversion) while maintaining $\gamma = 0.8$ regarding the CAPEX relation between solar and wind sources. Figure 7.7 shows that for all tested values of λ, Q does not exceed FEC as expected. Interesting to note, as λ increases from 0 to 1, the optimal x varies from 0.2228 to 0.3411, and M decreases from 0.6950 to 0.5816, respectively. These results suggest that the higher the risk aversion, the higher is hybridization and the lower is the transmission usage

In conclusion, our findings highlight the importance of considering risk preferences in the design and operation of hybrid power plants. By understanding the generator's risk aversion, we can make informed decisions about the optimal mix of energy sources to maximize economic benefits while minimizing risks.

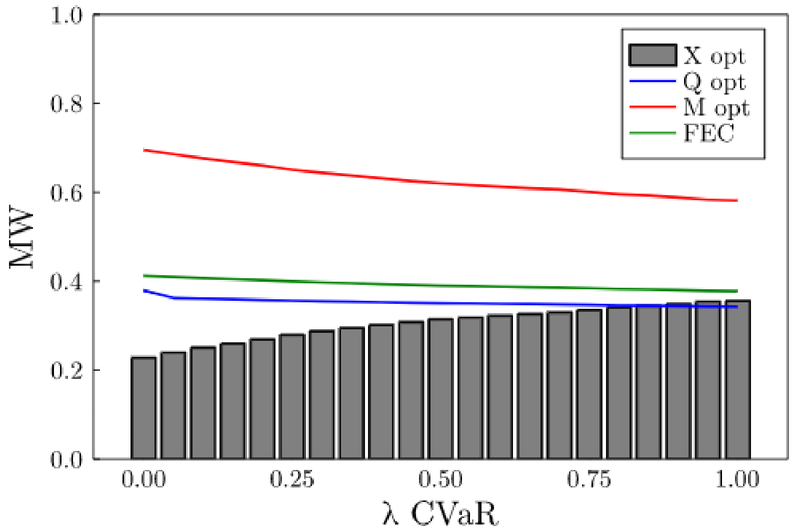

Figure 7.7: Risk Aversion, for $CAPEX\gamma = 0.8$, optimum x solar, M, Q and FEC according to $\lambda CVaR$.

8
Summary and Conclusions

This dissertation proposed a unified formulation for the firm energy certificates of renewables and hybrid power plants in Brazil. Based on that, a co-optimization tool for jointly defining the optimal network-access and forward contracting strategy was proposed and tested with realistic data from typical profiles of wind and solar generation. The proposed truncated expected-value-based firm energy certificate (TEV-FEC) constitutes the minimal change in the current regulation needed to make a coherent, unified, and non-discriminatory framework for renewables and hybrid power plants. Additionally, according to our Theorem 1, it also enjoys the relevant property of super-additivity, which creates the link between investment incentives in hybrid power plants and reducing transmission expansion costs.

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

- The co-optimization of NAC and forward contracting strategies is capable of providing relevant gains for the hybrid power producers.
- The reduction in the NAC with respect to the benchmark value (total installed capacity) is responsible for most of the monetary benefit, whereas the curtailed excess of energy is relatively low, thereby justifying the reduction in NAC fix expenditures.
- When disregarding CAPEX, the optimal joint strategy of forward and network-access contracting results in the minimum network usage for a hybrid plant that is composed of 54% wind and 46% solar generation (results valid only for the analyzed data).
- Co-optimizing network-access M and forward contract Q enhances the overall performance of a power plant, as demonstrated by a gain of 18% of equivalent certain in our case study.
- Based on typical values of CAPEX ($C^W = 4,000$ and $C^S = 3,200$) and generation profiles of wind and solar power plants in the Northeastern region of Brazil, hybridization can be not only the best economical

option for investors but also the one that provides the highest benefit for consumers in terms of reducing transmission costs. For instance, for the aforementioned CAPEX, the best strategy is $[M^* = 0.5968, Q^* = 0.3367, x^* = 0.3388]$.

- Adjusting the model to availability contract philosophy (emulating an availability contract scenario), we observe that hybrid power plants are less incentivized when compared to the quantity contract scenario. Because more complexities reach the generator's decision on the quantity contract scenario, this type of expansion tends to achieve a more cost-reflexive matrix, ultimately, more efficient.
- The higher the risk aversion, the higher is hybridization and the lower is the transmission usage.

For future research, we highlight as a relevant topic the study of the regulatory incentives and the optimal trading strategy of hybrid power plants considering more sophisticated FECs, e.g., the seasonal FEC introduced at the end of Chapter 5. Another interesting subject regards the hybridization idea can be expanded for a pool of renewable plants within a given bus of the system or within a "transmission-free" zone. In this case, the ideas proposed in this dissertation can be expanded for $n > 2$ units, and a cooperative game theory such as that proposed in [10] can be used to share the total FEC of the pool among sources, an issue not treated in this work. Finally, fostering commercial purposes, future improvement in the algorithm (6-5 to 6-11) can address existing hybrid power plants selecting yearly values of NACs considering the Brazilian regulatory rules.

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