



# Capacity Payments and Renewable Portfolio Investments: A Real Options Approach

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## ABSTRACT

The ongoing energy transition is increasing the share of renewable energy sources in electricity systems, raising concerns about resource adequacy and long-term investment incentives. Given the intermittent nature of renewable generation, investors face significant uncertainty related to electricity prices and production variability, which may influence investment timing and portfolio composition. In several liberalized electricity markets, capacity mechanisms have been introduced to mitigate these risks and ensure sufficient generation capacity. This paper evaluates how capacity payments and portfolio complementarities between renewable sources influence investment decisions under uncertainty. A real options analysis (ROA) framework is developed to model the option to defer investments in hydropower, wind power and combined hydro–wind portfolios. The model incorporates uncertainties related to electricity prices and generation output and is implemented using a binomial lattice approach with consolidated volatility estimates. The methodology is applied to the Brazilian electricity market (BEM), which is undergoing a liberalization process and preparing new capacity auctions. Results show that complementarities between hydropower and wind generation reduce investment risk and lower the option value of waiting. Diversified renewable portfolios allow investors to participate more competitively in capacity auctions while remaining resilient to market volatility, improving the effectiveness of capacity remuneration mechanisms.

**Keywords:** Investment Under Uncertainty, Real Options Analysis, Renewable Energy, Portfolio Production Complementarity, Capacity Mechanisms

**JEL Classifications:** D81, Q42

## 1. INTRODUCTION

Investments in renewable sources have experienced rapid growth since the 1990s and are expected to continue playing a crucial role in the global energy transition. Wind is expected to account for more than one-third of electricity demand by 2050, while hydropower will continue expanding in absolute terms (IEA, 2021; IRENA, 2020).

Despite competing for market share, wind and hydropower plants have strong potential to operate as complementary generation sources. Synergies among different energy sources, especially variable renewable energy sources (VRE), can help investors mitigate risks related to variability and uncertainty of production, such as discussed by (Camargo et al., 2016).

Electricity prices represent another important source of uncertainty for new investments in the power sector. Because of their connection to the physical world and inherent representation of supply and demand equilibrium, electricity prices will inevitably present some volatility and uncertainty. In that sense, many countries have introduced capacity mechanisms (CM), promoting special remuneration schemes, to restore incentives to investors and support resource adequacy in power systems.

While traditionally dominated by conventional plants, CMs have evolved to include renewables, storage, and demand response (Jimenez et al., 2025; Hohl and Prete, 2025). In mature markets, the regulator defines clear criteria for firm capacity, derating factors, and availability obligations, and investors must adapt

their portfolios to qualify. Examples include PJM and ISO-NE in the United States, the UK Capacity Market, and SEMO in Ireland (Byers et al., 2018; ISO-NE, 2024; SEMO, 2024).

The case study examines the BEM which is transitioning from a centralized auction-based model to a more liberalized framework with decentralized investments. As part of this modernization, the first capacity auction was held in 2021—focused mainly on thermal power plants—and a new round is planned for 2026. These mechanisms aim to safeguard system adequacy and stability while the sector advances toward a market-driven expansion model. The objective of this paper is therefore to assess how adequate levels of capacity payments (CP), when combined with portfolio complementarities, can enable investors to bid competitively while remaining robust against uncertainty. The intuition behind performing ROA is this: having options allows for gains on the upside of uncertainty and reductions on downside potential (Pless et al., 2016). ROA is commonly used to analyze renewable energy and portfolio investments such as discussed in (Boomsma et al., 2012; Passos et al., 2017; Makimoto and Takashima, 2023).

In the proposed model, the investor could exercise the option to defer an investment in a hydro-wind portfolio, comparing such hybrid combination, to hydro or wind standalone projects. The option to defer relies on assessing whether future market conditions are better than current ones, thus providing a greater net present value (NPV) for the project. Uncertainties in the proposed model are related to the spot price in the wholesale market, contract prices, and the generation of hydro and wind power plants.

Despite the extensive literature on capacity remuneration mechanisms and real option valuation of renewable investments, limited attention has been given to the joint interaction between portfolio complementarities and capacity payment design under uncertainty. In particular, there is a lack of studies quantifying how hydro–wind complementarities affect the real option value of deferral in emerging electricity markets transitioning toward capacity-based remuneration schemes. This paper addresses this gap by integrating portfolio theory and ROA into a unified framework to assess capacity payment adequacy from the investor’s perspective. Using the BEM as a case study, we evaluate how complementary generation patterns influence bidding strategies, opportunity costs, and optimal timing decisions under evolving market architecture.

By explicitly linking capacity payment sizing to option value reduction, this study contributes to the literature in three ways: (i) It quantifies the interaction between portfolio diversification and real option value; (ii) it provides a methodology for calibrating capacity payments consistent with private investment incentives; and (iii) it offers regulatory insights for emerging markets designing capacity mechanisms aligned with the energy transition.

This paper is comprised of five sections. Section 2 presents a literature review on capacity mechanisms, portfolio effect and investments in the energy industry using ROA. Section 3 presents an overview of proposed methodology and Section 4 the case study, sensitivity analysis and results for the BEM. Section 5

concludes our explanations and presents a review of policy extension recommendations, besides guiding future research on this area.

## 2. LITERATURE REVIEW

### 2.1. Capacity Mechanisms

Worldwide, a variety of market designs have emerged to better adapt market functioning to physical, economic, and political regional particularities. Despite the different market structures, a common concern to all policymakers was the maintenance of resource adequacy in the light of prices being practiced in liberalized markets promoting sufficient stimulus to new investments, besides proper market functioning itself, because of failures such as low demand flexibility.

In that sense, CM were introduced to address policymakers’ concerns regarding resource adequacy and security of electricity supply (Joskow, 2008; Cramton et al., 2013). (Chattopadhyay and Alpcan, 2016) classify electricity markets in two types, energy-only ones, in which electricity prices are the only driver to investments, and capacity-energy ones, in which additional remuneration is provided through CMs. (Rodilla and Batlle, 2012) discusses the paradox in needing regulator’s intervention to complement the electricity market to guarantee the supply in a deregulated electricity market.

In the past decades, a variety of CMs have emerged worldwide. (Erbach, 2017) divides them in two main types, the volume-based, in which policymakers define the volume of capacity needed and price is set by the market, and price-based mechanisms, in which policymakers set the price and let investors decide the capacity volumes. Among CM are strategic reserves, adopted by Germany, Belgium and Sweden (Holmberg and Tangerås, 2021), capacity obligations, adopted in France (RTE, 2021), reliability options, adopted in Colombia, ISO-New England, Ireland and Italy (Andreis et al., 2020) and, capacity payments, adopted in Spain (ACER, 2021). Some deregulated electricity markets promote capacity payments to all generation units, which is also referred to as a market-wide capacity mechanism or capacity market (Holmberg and Tangerås, 2021).

In some markets, there are discussions on redesigning and limiting the usage of CM because of concerns on power markets distortions. For example, The clean energy package of the European Union (EU) limits the abuse of CMs through the regulation (EU) 2019/943, which introduces two steps to check the mechanism real need and includes provisions to guide their design (Meeus, 2020). Cross-border participation in CMs in the EU are also discussed and incentivized (ACER, 2020).

In many markets, CM are also being reshaped in to foster energy transition and to address new power matrixes structures that are constantly evolving due to a higher penetration of VRE sources. (IRENA, 2019) suggests that innovative CM shall allow the participation of VRE sources and help promote flexibility in power systems by establishing adequate requirements, besides allowing the participation of demand response, energy storage

and interconnections. (Bhagwat et al., 2017) discusses the effectiveness of capacity markets in the presence of a high portfolio share of renewable energy sources and (Parmar and Darji, 2020) broadly discusses classifications and functioning of capacity markets with renewable capacity integration. Söder et al. (2020) discusses how wind power is handled in the regulation of capacity adequacy and its impacts on capacity markets for 14 countries' jurisdictions.

In the United States, VRE are allowed to participate in several capacity markets, such as independent system operators/regional transmission organizations (ISOs/RTOs) Pennsylvania-Jersey - Maryland Interconnection (PJM), ISO-New England (ISO-NE), Midcontinent ISO (MISO), and New York ISO (NYISO) (Byers et al., 2018). CM have also been introduced in some cases to promote the expansion of VRE, such as the case of Russia (Boute, 2012). In the United Kingdom, CM were also introduced to promote renewable energy expansion, however, in a hybrid police combined with contracts for differences (Onifade, 2016). In Ireland and Northern Ireland, capacity market rules set that variable generator units are not required to register in capacity auctions but can do it voluntarily (SEMO, 2021).

With the next auction planned for 2026, Brazil could align with international best practices by allowing broader participation. The Brazilian debate on firm capacity definitions resembles earlier discussions in US and Europe, showing how regulatory learning curves are repeated across contexts.

## 2.2. Portfolio Effect

Combining different power sources in a portfolio has been a relevant trading and investment strategy for energy companies to reduce risk and improve returns. More specifically, wind and hydro power complementarity have been intensively explored in previous studies because of its potential to smooth out the output patterns by combining hydropower flexibility with stochastic behavior of the wind power (Denault et al., 2009).

Some works discuss the complementarity of wind and hydro power in isolated systems such as (Bueno and Carta, 2006; Kaldellis, 2002), whereas others focused on modeling the portfolio effect in electricity markets such as (Bélanger and Gagnon, 2002), with some also discussing profit optimization and risk exposure reductions such as in (Ramos et al., 2013). In some countries the combination of hydro and wind power have also been incentivized in so called hybrid projects, such as in Australia (AEMO, 2019) and China (NEA, 2020). Especially in Brazil, where the case study was taken, hydro and wind patterns are known to present strong complementarity as discussed in (Cantão et al., 2017).

In Brazil, the hydro-dominated system creates a unique context: Wind generation tends to peak in dry periods, complementing hydropower output. Solar further balances seasonal and daily variability. This natural synergy mirrors portfolio strategies studied internationally, but with even stronger potential due to Brazil's large hydro base.

## 3. METHODOLOGY OVERVIEW

### 3.1. Real Option Analysis

An alternative commonly used for investment analyses, which overcomes some of the limitations of the traditional discounted cash flow (DCF) methodology, is ROA. It does not reject the traditional DCF methodology but complements it with regards to uncertainties incorporation and managerial flexibilities consideration, such as expanding, abandoning, or deferring a project. The singular characteristics of energy-related investments, such as irreversibility and exposure to multiple uncertainties, including price and production volatility, make ROA particularly suitable for project valuation. In the proposed model, the investor exercises the option to defer an investment in a hydro-wind portfolio, comparing such hybrid combination, to hydro or wind standalone projects. The option to defer relies on assessing whether future market conditions are better than current ones, thus providing a greater NPV for the project. It is modeled as an American call option, thus being possible to be exercised at any time before the option's expiration date (Trigeorgis, 1993). The project value with flexibility  $C$  is a function of project value  $V$ , the investment cost  $I$ , the risk-free rate  $r_f$ , the volatility  $\sigma$ , time to maturity and the number of periods  $N$  of the analysis.

$$C = C(V, I, r_f, \sigma, T, N) \quad (1)$$

In this model the approach was to implement the binomial lattice method based on probability theory (Cox et al., 1979), which uses discrete mathematics in option pricing, achieving isomorphic results to the Itô calculus used by Black-Scholes (Black and Scholes, 1973). To model uncertainties and estimate the project's volatility it is assumed the consolidated approach proposed in (Copeland and Antikarov, 2003). It was referred to as a "*consolidated approach*" in the sense that a single volatility measure is built up from different sources of uncertainties such as price and energy production. The volatility to be measured in this model relates to the percentage changes in the value of the project. In this case two assumptions are considered, first the marketed asset disclaimer (MAD) and second, based on Paul Samuelson's theorem (Samuelson, 1965), that properly anticipated prices fluctuate randomly. The MAD assumption is adopted under the understanding that electricity spot prices in Brazil are formed through a centralized stochastic dispatch model (NEWAVE), which embeds forward-looking expectations of hydrological conditions and system expansion. Although regulatory interventions exist, price formation incorporates anticipated fundamentals, supporting the use of stochastic modeling for project valuation. This way, the volatility can be estimated through the following expression:

$$\sigma = std\ dev \left( \ln \left( \frac{PV_t^i}{PV_0} \right) \right) \quad (2)$$

Where  $PV_t^i$  represents the present value of the underlying asset in instant  $t$  obtained at simulation scenario  $i$ , while  $PV_0$  is the asset value at the beginning of the analysis period.  $PV_t^i$  is given by the sum of expected cashflows ( $E(CF_t^i)$ ) in the period discounted by the rate of return of the project  $r$ .

$$PV_t^i = \sum \frac{E(CF_t^i)}{(1+r)^t} \tag{3}$$

In the proposed model, the  $CF_t^i$  are estimated through the free cash flow to the Firm methodology discussed in (Damodaran, 2006) considering revenues coming from bilateral electricity contracts ( $Rbc_t^i$ ) and capacity payments ( $Rbc_t^i$ ). Costs ( $OpC_t^i$ ) considered are related to parks operation and maintenance, grid and system specific charges, depreciation, and amortization ( $D \& A_t^i$ ), and the exposure in the spot market due to imbalances between contracts and power plants output volumes, which could be either positive or negative. The tax rate is considered constant over the whole period and capital expenditures ( $CAPEX_t^i$ ) due to power plant maintenance are also considered through the period  $t$ .

$$CF_t^i = (Rbc_t^i + Rcp_t^i - OpC_t^i) * (1 - Tax\ Rate) + D \& A_t^i - CAPEX_t^i \tag{4}$$

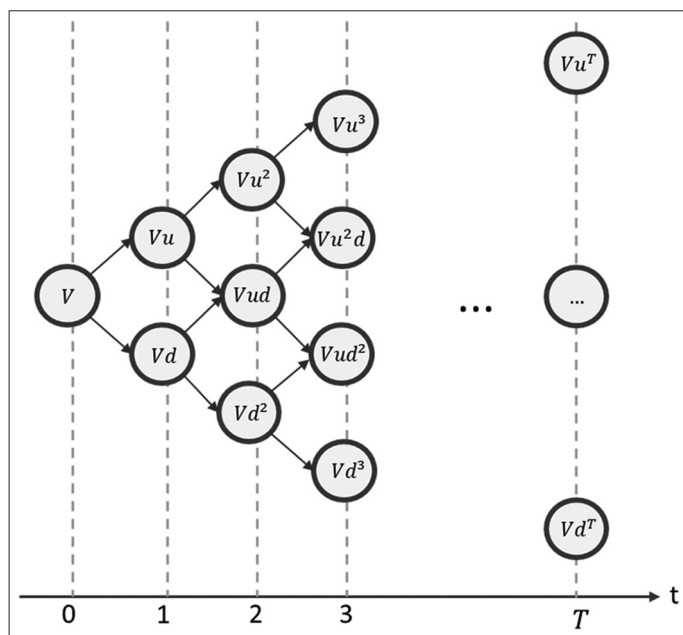
After estimating  $\sigma$ , the value of the project could go up and down in a present value event tree due to uncertainties behavior. Up and down movements,  $u$  and  $d$ , are mathematically described as follows (Cox et al., 1979):

$$u = e^{\sigma\sqrt{T/N}} \tag{5}$$

$$d = e^{-\sigma\sqrt{T/N}} \tag{6}$$

In the adopted model it is assumed that the volatility remains constant for different periods of the event tree, thus  $u$  and  $d$ , also do not change. The event tree (Figure 1) models how the value of the underlying asset may evolve in time based on the uncertainties combined in the volatility. Once the event tree has been built, the next step is to incorporate managerial flexibility creating a decision

Figure 1: Event tree



tree. At each node  $j$  of the decision tree, the option to invest or to wait is analyzed. Therefore, through the decision tree the payoffs of optimal decisions are calculated.

To value the option, we start from the last nodes on the event tree ( $t = T$ ). The decisions at these nodes are either to invest or not in the project, therefore being the maximum value between project's value  $V_{j,t}$  minus the investment cost  $I_T$  and zero:

$$C_{j,T} = \text{Maximum}[\{V_{j,T} - I_T; 0\}] \tag{7}$$

For all other nodes, the decision to invest is based on the comparison of the project value of each node minus the investment ( $V_{j,t} - I_{j,t}$ ) and the value of investing in the future, thus decisions taken in  $t + \Delta t$ . To value the real option, we implement the risk-neutral probability method in each node of the decision tree, prior to maturity  $T$ . This approach considers a hedge portfolio composed of one share of the underlying asset and shares of its option. Therefore,  $n$  is the hedge-ratio, so the portfolio becomes risk-free. For each node in  $t$ , prior to maturity  $T$ , the following decision is applied:

$$C_{j,t < T} = \text{Maximum} \left\{ \frac{uC_{t+\Delta t}^d - dC_{t+\Delta t}^u}{(u-d)(1+r_f)} \pm \frac{C_{t+\Delta t}^u - C_{t+\Delta t}^d}{(u-d)}; V_{j,t} - I_{j,t} \right\} \tag{8}$$

After all this recursive calculation, the first node  $C_0$  contains the value of project with the flexibility to defer the investment during the period  $T$ . Therefore, the option value itself, which we name  $OV$ , is the difference between  $C_0$  and the value of the project without any flexibility.

### 3.2. Uncertainties

Uncertainties in the proposed model are related to spot prices in the wholesale market, contract prices, and the generation of hydro and wind power plants. To rigorously evaluate the portfolio effect, the scenarios must consider the correlation between the wind and hydropower outputs, which can be accomplished using historical data to create scenarios.

In Brazil, the NEWAVE model (Maceira et al., 2018), developed by CEPEL (Center for Electrical Energy Research) is used for power systems planning, operation, besides being a relevant part of the spot price calculation by optimizing the centralized dispatch (Gonçalves et al., 2017). To generate spot prices scenarios, the NEWAVE model takes into consideration historical data from water flows since 1932 and current power system conditions regarding 'generation and transmission expansion, water reservoir situation, electricity demand projections, and expected generation from variable renewable sources.

Originally, wind power plants' output expectations are represented deterministically into NEWAVE. Therefore, we apply the methodology developed in (Witzler et al., 2016) to reconstruct wind generation's historical data, based on data accuracy verification, vertical exploration of wind series and calculation of Weibull's distributions to finally simulate the wind generation's scenarios.

Once having hydropower and wind generation scenarios from historical data, it is possible to generate spot prices scenarios based on these data but considering current power systems' conditions. For contract prices, we assume an average price based on the methodology developed in (Vitorino, 2011), which uses genetic algorithms to price electricity contracts based on the historical behavior of electricity market procurement and spot prices in Brazil.

## 4. CASE STUDY AND RESULTS

### 4.1. Brazilian Market Modernization

Recently, the Brazilian government has been promoting an important modernization process towards expanding electricity market liberalization. Among the modernization propositions is the creation of a capacity mechanism to assist an adequate volume of investments in the sector. Until today, most of the generation expansion in Brazil has been supported by regulated auctions in which the winners obtained long-term power purchase agreements (PPAs).

Because of market liberalization, regulated auctions may slow pace, and new projects should emerge through investors' initiative. As spot prices present high volatility, mostly due to climate and seasonal conditions, the proposed capacity mechanism must provide adequate remuneration to ensure the economic viability of new projects. In 2021, the Brazilian government approved a transitory mechanism to address the BEM's resource adequacy issue, and the first BCA (*Leilão de Reserva de Capacidade – LRCAP*) was held in the same year, mainly contracting thermal plants. The next auction is expected to take place in 2026, consolidating the long-term framework.

This approach, however, contrasts with capacity mechanisms in other countries that tend to be more technologically neutral, allowing a broad range of resources—renewables, demand response, storage, and thermal plants—to compete on equal terms (Frontier Economics, 2020; Kozlova and Overland, 2022). The current Brazilian model therefore risks limiting innovation and cost efficiency. To meet electricity demand expansion in Brazil, the installed capacity of wind sources is expected to grow 167% until 2029, and hydropower 9%, considering both small, medium-sized, and large projects, totalizing 34GW or almost 45% of total expected investments (EPE, 2019). Considering how representative investments in wind and hydro should be in forthcoming years and recent propositions of a capacity mechanism in Brazil, this work proposes a methodology to analyze how the new market architecture can foster investments in the correct direction of the energy transition process.

### 4.2. Capacity Payment Sizing

In this section, the implementation of the methodology proposed in Section 3 is presented for an investment in a hydro-wind portfolio in Brazil. The investor has the option to defer and to make an investment in either hydropower or wind standalone projects, or in both projects at the same time, thus in a hydro-wind portfolio. Decisions can be taken yearly during a period of 5 years.

Table 1 shows the investment and operation premises for both sites. Investment costs and capacity factors are based on historical data from regulated energy auctions in Brazil (ANEEL, 2020). Hydropower operation and maintenance (O&M) costs consider references from (EPE, 2018) and wind from (IRENA, 2018). The currency rate considered for all Brazilian data in this work is R\$3.84/US\$.

To build up  $OpC_t^i$ , grid costs, other system charges and *D&A* are considered. Grid cost for both plants are 2 US\$/kW/month, based on tariffs disclosed to 2019's energy auction (ANEEL, 2019). Other system charges depend on the type of source and specific power plant characteristics being detailed in (ANEEL, 2016). Besides, depreciation is considered linear and ending at the same time as the power plant's concession period.

Revenues are the sum of bilateral contracts, sales and capacity payments. For bilateral contracts, the power plant is regulatorily allowed to sell up to 100% of its firm energy certificate (FEC). For this work, we assume the FEC to be the multiplication of the power plant installed capacity by its capacity factor and that both plants sell the totality of their FEC.

In Brazil, because of the centralized dispatch and strong seasonality, most hydropower plants enroll in the energy reallocation mechanism (ERM). The ERM is a risk mitigation mechanism that exchanges amounts of energy among its participants, so that at the end of 1 month all of them have the same exposure to hydrological risk, independent of their geographical position and the physical dispatch that have been defined by the ISO. For this reason, we assume the hydropower plant to follow this generation's behavior. For further details see (Susteras et al., 2011) and (Griebenow and Ohara, 2019).

For the wind power plant, it is assumed a generation profile of the city of Macau in Rio Grande do Norte state and build scenarios using methodology described in (Witzler et al., 2016). Figure 2 shows the average generation profile for both hydro and wind plants and the values expected to exceed 5% (P05) and 95% (P95) of the scenarios. Generation is expressed as a percentage of the FEC seeking better illustration of the complementarity pattern between hydro and wind sources chosen.

To better understand the impact of prices volatility, it is assumed that power plants are procuring only short-term bilateral contracts. Besides, it is considered both power plants to be exposed to the spot market due to imbalances between contracts and power plants' output volumes, which could be either positive or negative. For capacity payments, we assume them being a yearly fixed payment in R\$/MW during the whole concession period.

**Table 1: Power plant general characteristics**

	Wind	Hydro
Installed Capacity (MW)	100	300
Capacity Factor (%)	45%	55%
Investment Cost (million US\$/MW)	1.2	1.8
Concession Period (years)	20	30
Operation & Maintenance Costs (US\$/kW/year)	25	15

First, the study analyzes the investment in a hydro power plant project. Figure 3 compares traditional NPV results to the ones using ROA for different levels of capacity payments. The option to defer has value in every scenario where the ROA result is greater than the traditional NPV. Beyond the threshold when both analyses present the same value, that is the option value is zero, investment can be made with no opportunity cost.

Results show that hydro power plant investments are likely to require capacity payments to be made in a new electricity market scenario where long-term PPAs from government auctions are no longer available. The results indicate that an annual fixed payment of approximately R\$400 thousand/MW is required to reduce the real option value of waiting to zero, thereby eliminating the opportunity cost of deferral. From a real options perspective, this threshold represents the minimum remuneration necessary to compensate investors for exposure to price and production volatility in a liberalized market environment. In energy-equivalent terms, this corresponds to approximately R\$83/MWh, highlighting the economic magnitude of capacity remuneration relative to expected wholesale electricity prices.

To isolate the portfolio effect, the option to defer investment in wind and hydropower as standalone projects is compared with the

option value obtained when both projects are developed jointly as a hydro–wind portfolio. First, the wind power plant is considered to receive no capacity payments, what results in a negative NPV of R\$49.4 million and an option to defer the investment of R\$ 78.8 million. Wind power option to defer value is added to the previous hydropower plant standalone scenario and compared to the simulation where wind and hydro projects combine cashflows in one hydro–wind portfolio as Figure 4 shows.

The results show that incorporating 100 MW of wind capacity into the hydropower project enhances total expected revenues while requiring only limited additional capacity remuneration, maintaining the hydropower payment at approximately R\$400 thousand/MW-year. Importantly, this joint configuration alters the project’s risk profile without increasing exposure to underlying uncertainties in electricity prices and generation.

The key result is that the hydro–wind portfolio reduces the dispersion of expected cash flows due to seasonal complementarity, which in turn decreases project volatility. Since option value is positively related to volatility, the reduction in uncertainty lowers the value of waiting and accelerates optimal investment timing. In other words, diversification acts as a volatility-dampening mechanism, reducing the compensation required through capacity

Figure 2: Wind and hydropower generation profiles

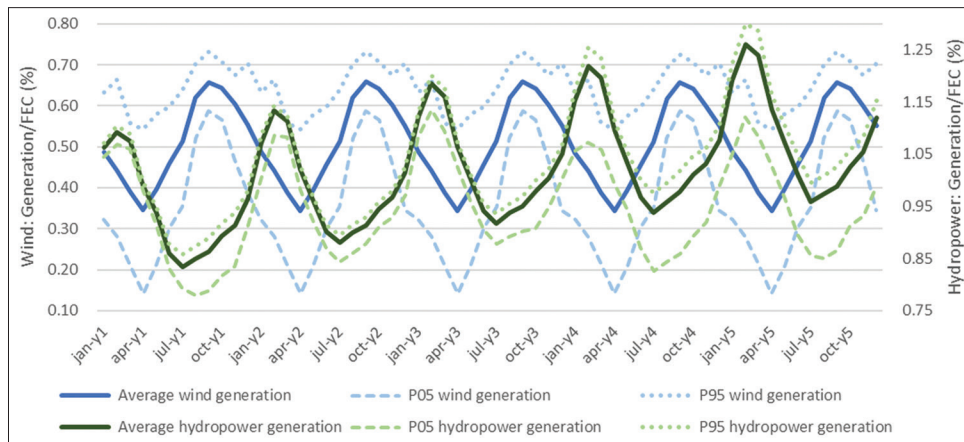
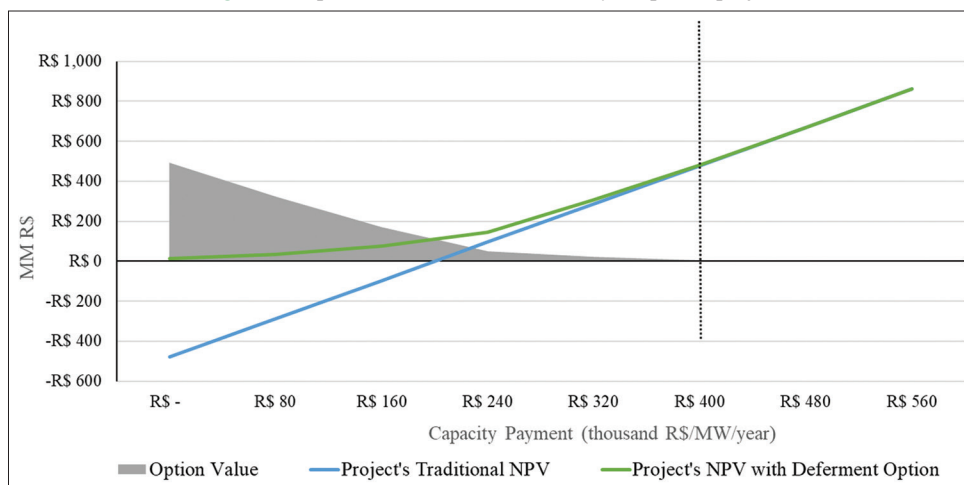
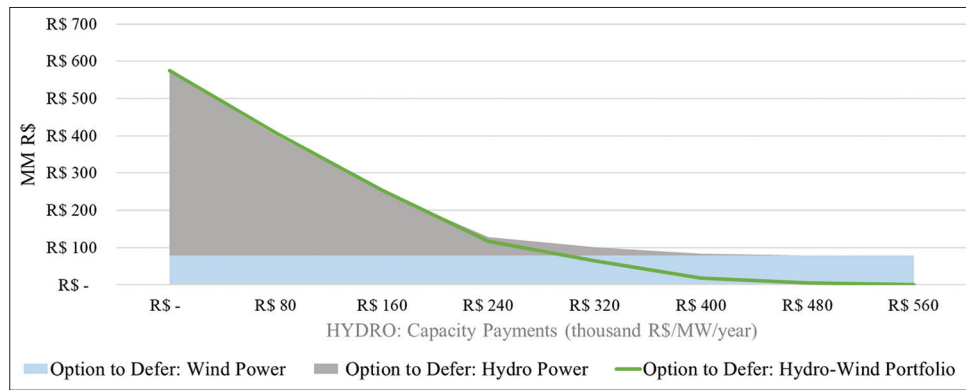


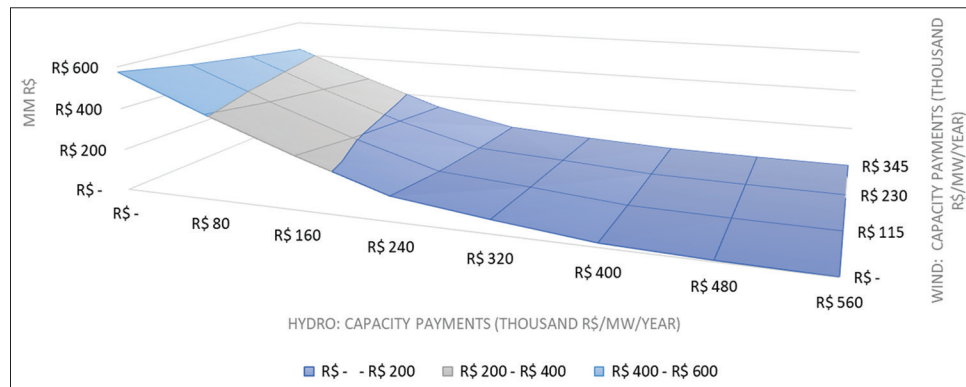
Figure 3: Option to defer investment in hydro power project



**Figure 4:** Comparing options to defer investment in projects alone and in a hydro-wind portfolio



**Figure 5:** Option to defer investment in a hydro-wind project



payments. To a last analysis, the study assumes both wind and hydro power projects receive capacity payments in a hydro-wind portfolio, as Figure 5 shows. As expected, when capacity payments for the wind project increase, the option to defer investment in the hydro-wind portfolio decreases. However, the results show that different combinations of capacity payments for the different sources could access the same results when it comes to seeking zero opportunity cost.

The findings indicate that eliminating the opportunity cost of deferral requires a capacity payment of approximately R\$400 thousand/MW-year for standalone hydropower, with alternative hydro-wind combinations achieving similar investment incentives at R\$320 thousand/MW-year for hydropower or R\$345 thousand/MW-year for wind. In energy-equivalent terms, these values correspond to approximately R\$66-88/MWh, underscoring the economic magnitude of capacity remuneration relative to expected wholesale electricity prices and highlighting its central role in investment viability under uncertainty.

When capacity payments are evaluated on a portfolio basis, the results reveal an important efficiency gain. By incorporating 100 MW of wind capacity into the 300 MW hydropower project, the total contracted capacity increases to 400 MW, while the required remuneration per MW can be reduced through alternative combinations without increasing the opportunity cost of investment. When expressed in energy-equivalent terms, the weighted average cost falls to

approximately R\$71/MWh, compared to R\$83/MWh in the standalone configuration.

These findings indicate that capacity remuneration can be reallocated across technologies without altering investment timing incentives, provided that portfolio complementarities are properly internalized. From a regulatory standpoint, this suggests that technology-neutral auctions may overlook cost-reducing interactions between resources. Designing capacity mechanisms that recognize diversification benefits could therefore achieve adequacy targets at lower total remuneration levels.

## 5. CONCLUSION

The utilization of ROA in this study underscores its effectiveness as a valuable tool for both regulators and investors seeking to analyze the adequacy of capacity payment prices in relation to their strategic objectives. By explicitly incorporating stochastic electricity prices, generation complementarities, and managerial flexibility, the proposed framework captures key structural features of modern liberalizing electricity markets. The alignment of capacity payment prices obtained through this methodology with those observed in regulated auctions further underscores its practical relevance and applicability in real-world scenarios. More importantly, the results demonstrate that portfolio complementarities materially affect the real option value of deferral, thereby influencing optimal bidding behavior in capacity auctions.

From a regulatory perspective, the findings suggest that capacity remuneration mechanisms should not be designed under a technology-isolated logic when complementarities across renewable sources exist. By leveraging such analyses, regulators can craft more informed strategies regarding pricing and product offerings across diverse power sources, ultimately aiming for a balanced expansion mix while maintaining tariff moderation. Accounting for diversification effects may reduce overcompensation risks and improve allocative efficiency in capacity procurement. Additionally, investors can capitalize on the proposed methodology to refine their strategies for participating in capacity auctions, thereby enhancing their ability to navigate market dynamics and capitalize on investment opportunities effectively when searching for optimized portfolio of renewable energy.

Future research should extend the framework to include storage technologies, demand response participation, and endogenous contract structures. By expanding the scope of analysis, researchers can explore avenues for further enhancing the attractiveness of the methodology and addressing other key sensitivities crucial to the market. Such extensions would contribute to a more comprehensive understanding of how capacity mechanisms can be aligned with decarbonization pathways while preserving investment efficiency under deep uncertainty.

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