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Optimizing Price Markup: The Impact of Power Purchase Agreements and Energy Production Uncertainty on the Economic Performance of Onshore and Offshore Wind Farms

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ABSTRACT

Wind energy is rapidly expanding its capacity as part of the global energy transition. To ensure economic viability, wind energy projects increasingly rely on risk mitigation strategies. While power purchase agreements (PPAs) manage spot market price variability, wind farms still face energy production uncertainty, directly impacting the quantity of energy generated. This study presents a comprehensive analysis of the price markup for onshore and offshore wind farms, considering energy production uncertainty under PPA and non-PPA scenarios. The study examines key metrics such as equilibrium prices, price markups, internal rate of return (IRR), net present value (NPV), and their correlation to energy production risk. Results demonstrate that PPAs significantly alter the relationship between price markup and variability. Offshore wind farms can potentially benefit more from PPAs compared to onshore, especially at lower levels of wind energy variability. However, as variability increases, the risk mitigation provided by PPAs diminishes, and both onshore and offshore wind farms may require higher price markups for financial viability. These findings highlight the necessity of carefully designed PPA structures and pricing strategies to ensure long-term competitiveness and sustainability of wind energy projects.

Keywords: Power Purchase Agreement, Onshore, Offshore, Wind Energy, Internal Rate of Return
JEL Classifications: Q42, D81, G30

1. INTRODUCTION

The global move towards sustainable energy is driven by the challenges of climate change and overreliance on fossil fuels. Consequently, wind energy has been serving a crucial role in this transition with expected substantial growth in both onshore and offshore capacities globally.

By 2031, wind and solar power are expected to add approximately 9 GW to the Brazilian current installed capacity (Plano Decenal de Expansão de Energia, 2022). As one of the leading producers of sustainable energy, the country has a significant wind power potential (Pontes et al., 2023; De Assis Tavares et al., 2020; Turkovska et al., 2021; Lozer dos Reis et al., 2021) and high-capacity factors (Farkat Diógenes et al., 2020).

However, because of the competitive nature of energy markets, renewable energy developers are compelled to accept greater risks and lower returns (Dukan and Kitzing, 2021). There are challenges in establishing the economic feasibility of wind energy within auction mechanisms, particularly concerning the accurate quantification of bid prices (Stetter et al., 2020).

A variety of factors contribute to the challenges associated with wind energy, including level of competition, speculative bidding behaviour, and allocation and production uncertainties. In wind energy auctions, participants encounter several difficulties, including the uncertain and stochastic nature of wind resources, which may have a significant impact on the economic viability of wind energy projects by introducing additional risks that bidders must consider when calculating equilibrium prices (Martín et al., 2020).

There is a potential for a winner's curse in wind energy auctions due to overbidding and underbidding, which both require strategic pricing approaches to effectively manage the risk. Low bid prices, as demonstrated by (Martín et al., 2020), indicate a highly competitive environment. Although this scenario may be beneficial in terms of reducing energy prices, it creates risks to investors that may result in the abandonment of projects. Consequently, it is essential to assess the economic viability of wind energy projects using the best available information on potential risks.

Inexperienced participants present a tendency to bid below the Nash equilibrium which leads to underbidding, whereas experience is associated with decreased tendencies to overbid, which suggests that there is a learning curve (Stephenson and Brown, 2021). The Cobb-Douglas utility function has been applied by (Tan and Liu, 2022) to illustrates how bidders' preferences between winning probabilities and profit maximization influence their decisions, potentially leading to strategic overbidding or underbidding. Research has shown that information asymmetry in auctions and the opportunity costs associated with acquiring information can lead to overbidding due to under-informed decision making (Freeman et al., 2020).

The complexities of bidding strategies in renewable energy auctions have been the focus of several studies that emphasized the variety of approaches taken by participants, including both non-strategic and strategic bidding behaviours (Gao et al., 2021; (Zhu et al., 2021; Afshar et al., 2018; Swider and Weber, 2007; Fanzeres et al., 2019; Takano et al., 2018) that reveals a complex landscape where auction design (Matthäus, 2020; Anatolitis et al., 2022; Del Río and Kiefer, 2023) and energy production uncertainties (Shojaabadi et al., 2022; Balaguru et al., 2021) significantly influences bidder tactics and the overall effectiveness of the auction process.

It is important to note that despite the numerous uncertainties which investors face, the long-term variability of wind energy production stands out as a unique, non-diversifiable risk. In contrast to operational efficiencies, which vary depending on an investor's maturity level, wind intermittency remains unavoidable.

Even the most competitive and reliable auction winner will inevitably face the uncertainty associated with wind intermittency, which should be adequately addressed in the price to maximize the possibility of economic success. To assess the long-term wind energy potential of a site, a comprehensive assessment must be conducted. In addition, the quantity of energy contracted through PPAs can also have a significant impact on the project's revenue. In the context of wind energy economic valuation, the role of PPAs has not been adequately explored in relation to mitigating wind uncertainty and shaping appropriate pricing strategies.

The purpose of this study is to provide a comprehensive economic analysis of the expected financial impacts in wind energy projects by using a stochastic discounted cash flow (DCF) method to calculate financial metrics such as the IRR and NPV. The DCF method is widely used to analyse project economic viability (Azevêdo et al., 2021; Perrelli et al., 2023; Carvalho et al., 2020; Yang et al., 2020; Martínez-Ruiz et al., 2020). This research can contribute to the growing body of knowledge in wind energy economics and promotes the development of improved pricing strategies.

2. LITERATURE REVIEW

The importance of auctions has been highlighted in numerous studies, including the diversification of Colombia's hydro-dominant energy matrix (Moreno and Larrahondo, 2020) and European renewable energy policies (Anatolitis et al., 2022). In addition to policy shifts in the United States and China's commitment to renewable energy, Europe's desire to replace fossil fuels is a key factor for the anticipated growth of 680 GW of wind capacity by 2027, including 35.5 GW offshore (Global Wind Report, 2023).

The offshore wind auctions, crucial for decarbonization, have awarded approximately 53 GW worldwide by 2021, and over 200 GW are expected by 2030. As costs and subsides decline, new questions arise about optimal auction designs (Jansen et al., 2022). According to (Del Río and Kiefer, 2023), the success of an auction is heavily dependent upon its design.

The impact of auction design elements on renewable energy auction effectiveness was investigated by (Matthäus, 2020). According to the author, prequalification measures and penalties significantly increase realization rates. Wind developers in Europe are open to citizen participation in renewable energy auctions, but they require higher risk premiums as they offer citizens more shares, according to a study that examined how auction designs affect developers' risk perceptions (Côté et al., 2022).

An analysis of compliance incentives in renewable energy auctions in South Africa and Europe was conducted by (Kitzing et al., 2022). The results showed that price convergence was possible despite different country risks through strict incentives and proper auction design. Also, remuneration scheme designs, and low auction prices drive price risk, potentially worsening financing conditions (Dukan and Kitzing, 2021).

Brazilian offshore wind has immense potential, especially on the Southeast and South coasts (De Assis Tavares et al., 2020). A study by (Lozer dos Reis et al., 2021) indicates that the Northeast region has the highest potential and lowest levelized cost of energy, being a preferential area for offshore wind development.

A market based on auctions is susceptible to overbidding (in which buyers submit bids well above the true value) and underbidding (in which buyers submit bids well below the true value) which can result in inefficient market outcomes and distortion of the price signal. According to (Stephenson and Brown, 2021), inexperienced participants bid below Nash equilibrium predictions and exhibit cyclical bidding behavior, with greater instability in two-prize auctions. The research suggests that increased experience may reduce overbidding tendencies and highlights the value of evolutionary models in capturing auction complexities. Costly information acquisition can impact overbidding, known as the "bidder's curse," according to a study that integrated this concept into auction theory (Freeman et al., 2020).

A suitable pricing strategy can assist participants in adapting and determining the optimal bid that maximizes their chances of profitability and avoids overbidding and underbidding, leading to a reliable price indicator. The literature emphasizes the significance of developing and refining bidding tactics in renewable energy auctions. Numerous research works have suggested various approaches to bidding with the aim of enhancing economic results and maximizing profits. Numerous studies have concentrated on day-ahead markets, where daily bidding takes place. A stochastic framework incorporating uncertainties in power production using bid prices to model wind power plants and EV aggregators' bidding strategies in a day-ahead electricity market was presented in (Gao et al., 2021). An adaptive robust adaptive integrated bidding strategy was proposed in (Aghamohamadi and Mahmoudi, 2019), which demonstrated superior performance when compared to single-energy strategies in multiple day-ahead markets.

A bidding strategy for wind power producers and electric vehicle aggregators in day-ahead markets has been proposed by (Shojaabadi et al., 2022). The authors used stochastic optimization, genetic algorithms, and conditional value at risk to manage wind power uncertainty and optimize EV charging, highlighting the benefits of integrating EVAs to enhance WPP market competitiveness. The use of genetic algorithms has also been applied by (Motamedi Sedeh and Ostadi, 2020) along with Monte Carlo simulations (MCS) into a hybrid bidding strategy model for the Iran's day-ahead market that achieved higher profits than simple simulations.

Researchers have also examined bidding tactics in sealed-bid auctions, where participants submit their bids simultaneously without knowing what the other participants are bidding for, with a focus on pay-as-bid and contracts for difference (CfD) auctions. Offshore wind developers' bidding strategies in CfD auctions involve balancing the risks of overbidding (contract loss) and underbidding (winner's curse), according to a simulation study by (Kell et al., 2023). The methodology effectively estimates auction outcomes, with a simulation projecting a strike price 5% higher than the actual awarded price, emphasizing the critical balance between competitive bidding and project feasibility to mitigate non-realization risks.

A computational approach to optimize bid shading in first price sealed-bid auctions has been proposed by (Fagandini and Dierickx, 2022), highlighting how bidder population asymmetries and naive bidders significantly affect strategies. The authors demonstrated that overlooking naive bidders can result in suboptimal bidding, emphasizing the importance of accounting for complex behaviors and market conditions to maximize profits effectively.

A linear programming method has been proposed by (Mazzi et al., 2018) to optimize the offering curves of price-taker conventional producers in pay-as-bid electricity markets to increase profits. A methodology for creating revenue-maximizing bids in sealed-bid uniform-price auctions with uncertain competitor bids was presented by (Fanzeres et al., 2019). The approach significantly reduced risk and accurately estimated profit-maximizing bids under price uncertainty. In (Zhu et al., 2021), the authors analyzed optimal renewable auction bidding prices using a real options-based preemption game model and found that despite near-zero optimal prices with many participants, investors may still bid aggressively, harming immature projects.

The Multiagent Q-Learning approach proposed by (Chiu et al., 2022) outperformed model-based methods by eliminating unrealistic assumptions and considering bidding strategies' impact on the market. An examination of the optimal bidding process in European electricity markets, focusing on Germany, has been conducted by (Narajewski and Ziel, 2022). The authors evaluated profit maximization considering price impacts and transaction costs. Findings suggest minimizing price impact is more profitable than arbitrage, underscoring the need for complex strategies for significant market influencers.

The DCF is commonly used in finance and investment analysis to determine the economic viability of long-term projects. Using NPV and MCS, (Carvalho et al., 2020) evaluated the financial risk associated with early or late completion of wind-photovoltaic integrated power plants on the Brazilian energy market. It was found that delays considerably increased the likelihood of a failed business, while early completion was more beneficial for systems that had a higher proportion of solar power.

A systematic literature review has been performed by (Azevêdo et al., 2021) to identify the main factors impacting the economic feasibility of wind energy investments. The authors analyzed 120 papers and identified 23 key factors related to location, economic, political, climate, and technical aspects. The findings provided insights for researchers and investors to assess wind project viability.

However, further exploration is needed regarding pricing strategies for long-term wind energy projects based on different PPA scenarios considering energy production uncertainty. This study attempts to fill this gap by incorporating wind intermittency into cash flow analysis and providing a method for adapting prices in response to wind uncertainty.

3. MATERIALS AND METHODS

This section presents the DCF model to estimate the economic performance and risk profiles of onshore and offshore wind farms with and without PPAs. Energy production and costs were estimated based on the premises of the Brazilian energy research company (EPE) (Parâmetros de Custos - Geração e Transmissão, 2022). As a public institution affiliated with the Ministry of Mines and Energy, EPE conducts studies and research to assist in the planning and development of Brazil's energy sector.

Table 1: Energy production and cost premises

Wind farm	CAPEX range BRL/kW	P50 range (%)	O and M (BRL/kW/year)	Taxes/sectoral charges (BRL/kW/year)	Investment disbursement period (months)
Offshore	9.800-18.600	32-62	360	415	36
Onshore	3.200-5.500	38-47	90	145-155	24

The onshore and offshore wind farms have been analyzed separately, assuming each has an installed capacity of 100 MW. Based on the robust performance of the Gaussian process for wind production forecasts (Wen et al., 2022; Cai et al., 2020), the energy production estimate in this study has been based on a Gaussian distribution with a mean of P50 and standard deviations of different levels.

3.1. Model Dynamics

The results are obtained using Monte Carlo simulation with 600 iterations to analyze the financial performance of wind farms under uncertain energy generation scenarios, both with and without the presence of a PPA. In each iteration, the stochastic variable P50 (σ) is randomly sampled from the onshore and offshore distributions.

Table 1 presents the specific characteristics of each wind farm according to EPE (Parâmetros de Custos - Geração e Transmissão, 2022):

Where BRL stands for the currency Brazilian real. In this study, the P50 for offshore and onshore generators was estimated to be 62% and 47%, respectively. Considering the specificities of each wind farm, the model calculates the price markup to achieve P (NPV <0) = 5% for every standard deviation from 5% to 20% in steps of 1%. This is equivalent to setting the price markup such that the IRR equals the cost of capital when NPV is zero. Within the MCS, equilibrium price adjustments are made iteratively to maintain this condition.

As a result, the model ensures that the wind farm's financial performance is evaluated using consistent risk criteria, maintaining the probability of a negative NPV (or equivalently, an IRR below the cost of capital) at 5%. Using this approach enables a fair comparison of the wind farm's profitability and risk profile, as measured by IRR, across a range of levels of energy generation uncertainty and PPA obligations.

3.2. Scenarios

Onshore and offshore wind farms were modelled using the following scenarios:

1. Without PPA: When there is no PPA in place, the entirety of the energy generated is sold by the equilibrium price, which varies based on the standard deviation of the energy production.
2. With PPA: When a PPA is in effect, a fixed amount of energy, based on the physical guarantee specified in Table 2, must be delivered to fulfill the agreement, regardless of the energy generated.

The Table 2 presents the PPA physical guarantee (contracted energy) for the onshore and offshore wind farms:

Table 2: Physical guarantee on PPA

Standard deviation (%)	Physical guarantee onshore (MW)	Physical guarantee offshore (MW)
5	40.59	55.59
6	39.31	54.31
7	38.03	53.03
8	36.75	51.75
9	35.47	50.47
10	34.18	49.18
11	32.90	47.90
12	31.62	46.62
13	30.34	45.34
14	29.06	44.06
15	27.78	42.78
16	26.50	41.50
17	25.21	40.21
18	23.93	38.93
19	22.65	37.65
20	21.37	36.37

Table 3: Economic modelling

Component	Nature	Source
Revenue	Probabilistic	EPE
O and M	Deterministic	EPE
Sectoral charges	Deterministic	EPE
Income taxes	Deterministic	EPE
Loan cash flow	Deterministic	DBA
PPA obligation	Probabilistic	DBA
CAPEX	Deterministic	EPE

In the Brazilian electricity sector, the concept of physical guarantee plays an important role in the commercialization of energy since it determines the maximum volume of electrical energy that a generator will commit to delivering to its customers. The physical guarantee is 0defined by the regulations of the ministry of mines and energy (MME), and it is a certificate that specifies the maximum amount of electrical energy that can be traded by each power plant. Based on factors such as a power plant's capacity and overall government criteria for the security of the system's supply, physical guarantees represent the maximum amount of electrical energy a specific power plant or energy import project can reliably supply to the Brazilian grid. In this study, the 10th percentile (P10) of the Gaussian distribution of energy production was used to calculate the physical guarantee of each wind farm.

If there is a discrepancy between the energy produced and the PPA physical guarantee, the difference will be reconciled using the equilibrium price. The surplus energy will be sold at the equilibrium price when the energy production exceeds the PPA allocation. Alternatively, if the energy production does not exceed the PPA allocation, the necessary energy will be purchased at the equilibrium price to fulfill the PPA obligations.

The allocated energy decreases as the standard deviation increases. This study considered for this scenario the PPA price as 10% higher than the deterministic equilibrium price. In other words, at first glance, it seems beneficial for the seller to secure 10% of its energy on a long-term contract to assure a PPA price that is 10% higher than the market rate. However, failure to deliver the contracted energy will result in the project being forced to purchase energy in the spot market at its markup price, which will negatively impact the project's cash flow.

3.3. DCF Model

Table 3 presents the DCF model components used in this study:

Based on the inherent uncertainty associated with each component, the nature column categorizes each as either probabilistic or deterministic. Components with probabilistic values are those whose values are subject to random variation and cannot be predicted precisely, while components with deterministic values have fixed, known values.

As for revenue, it is classified as probabilistic since the revenue generated by a wind farm is directly dependent on the intermittent nature of the wind, which is considered for this study as the standard deviation. The PPA obligation is also classified as probabilistic since the wind farm may not always be able to generate and deliver the contracted amount of energy due to wind variability.

The Source column indicates the source of each component in the economic model. The term EPE is used to refer to data derived from the Energy Research Company, while DBA stands for variables that have been defined by the authors. Loan cash flow and PPA obligations are not governed by a specific guideline and may vary according to the situation.

This study considered 80% of the CAPEX to be financed at a flat rate of 7.5% per year with an 18-month grace period, a 24-year repayment term, and a single disbursement at the beginning of the 2nd year of the cash flow. Considering that the terms of a PPA are typically confidential between the buyer and seller, the assumptions regarding the PPA in this study are fictitious and serve the purpose of the analysis. Real-world PPAs are negotiated between the parties involved and are not publicly disclosed.

For the PPA obligations, it was assumed that if the seller fails to deliver the contracted amount of energy in each month, they must immediately purchase the shortfall from the market to fulfil their obligation under the PPA. This is a simplified assumption for the purpose of this study, since actual PPA contracts may have different clauses or provisions for dealing with under-delivery or non-performance.

Equation 1 presents the revenue as the stochastic component of the model:

$$Revenue_m = \theta[PPA_q\,(\partial).PPA_{price} + \omega.P_{eq}\,(\partial)] + (1 - \theta).\ P50\,(\partial).P_{eq}\,(\partial) \quad (1)$$

Where:

$Revenue_m$ is the total revenue for a given period;

$PPA_q\,(\partial)$ is the quantity of energy sold through the PPA according to the Table 2;

PPA_{price} is the price of energy sold through the PPA which is 10% higher than the deterministic price which is calculated at the first step of the model without regard to uncertainty;

θ is a dummy variable that equals 1 if there is a PPA and 0 otherwise;

ω represents the difference between the produced and contracted energy;

P50 (σ) is the stochastic variable representing the 50th percentile (mean) of energy generation as a function of the standard deviation (σ);

$P_{eq}\,(\partial)$ is the price of which P (NPV <0) = 5% for every standard deviation.

4. RESULTS AND DISCUSSION

In this section, the results of the economic evaluation of onshore and offshore wind farms are presented and analyzed, considering scenarios with and without PPAs. An emphasis is placed on selected important factors, such as equilibrium prices, price markups, and IRR ranges as well as their correlation with P50 values and standard deviations.

4.1. Onshore and Offshore Wind - without PPA

Based on this analysis, the deterministic equilibrium prices, calculated with a standard deviation of zero, vary significantly, with offshore prices much higher (BRL 400) than onshore prices (BRL 151). In part, this difference can be attributed to the higher costs of offshore wind farms that were not adequately compensated by the higher offshore energy production.

The Figure 1 illustrates the price markup, average IRR (IRR avg), IRR range, and the 5th percentile (P5) of the IRR distribution for the Onshore without PPA scenario.

As the standard deviation of wind production increases from 5% to 20%, the energy production becomes more variable, resulting in a more volatile IRR and an increase in the average IRR. The IRR Range, defined as the difference between the maximum and minimum IRR, increased from 4.58% to 23.36%. The model adjusts the equilibrium price at each standard deviation level to maintain the NPV <0 for 5% of the cases. This is achieved by setting the equilibrium price such that the 5th percentile of the IRR distribution remains constant (red line). When the IRR falls below the cost of capital, the NPV becomes negative. Therefore, by ensuring that the IRR is below the cost of capital 5% of the time, the NPV is kept negative for 5% of the cases. The constant P5 line confirms that the equilibrium price is being accurately repriced for different levels of volatility, with higher volatility leading to higher prices to compensate for the increased risk.

The Figure 2 illustrates the offshore scenario without a PPA. As in the previous case, the price markup increases as the standard deviation increases, while the IRR range widens as the average IRR increases.

Figure 1: Metrics for onshore without power purchase agreement

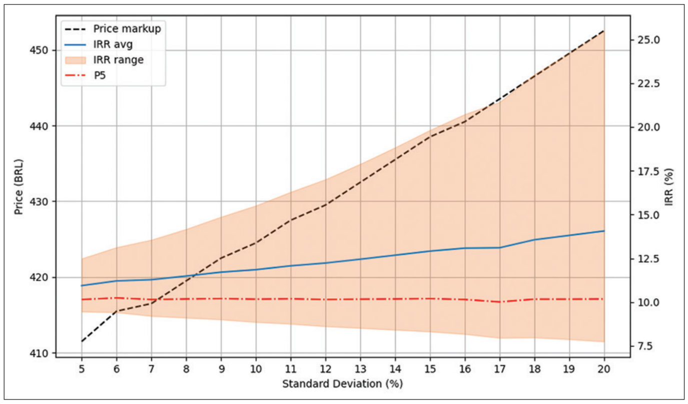
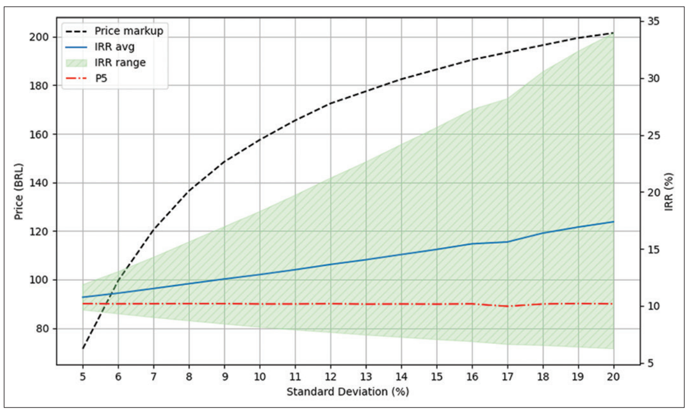


Figure 2: Metrics for offshore without power purchase agreement



The price markups for onshore and offshore wind farms increase in line with standard deviation, but at different rates. Based on a standard deviation of 20%, the offshore price is 9.96% higher than its initial price, while the onshore price is 14.60% higher. As a result, the price markup for offshore wind farms is less sensitive to variations in energy production than for onshore wind farms.

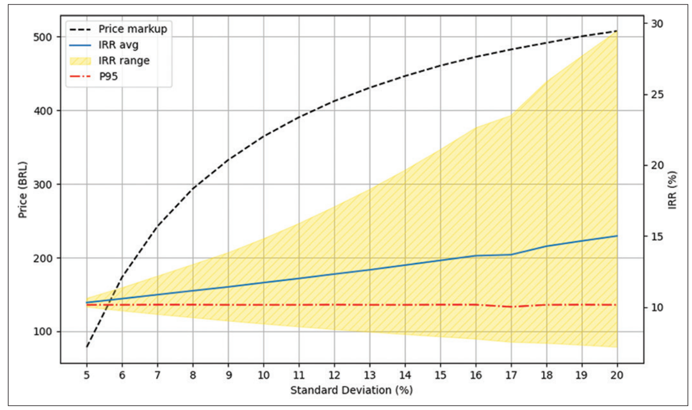
The maximum level of 20% standard deviation used in this study represents a greater proportion of the P50 of the onshore than the offshore wind farm. As a result, the onshore may be more sensitive to changes in energy production variability, resulting in a higher price markup to maintain the model NPV criteria.

The price markup for both the onshore and offshore wind farms is relatively inelastic with respect to changes in standard deviation. However, the elasticity of the offshore wind farm is slightly lower than for the onshore wind farm, indicating that the price markup for the offshore wind farm is slightly less responsive to changes in standard deviation compared to the onshore wind farm. This suggests that the relationship between standard deviation and price markup is more stable for the offshore wind farm than for the onshore wind farm.

4.2. Onshore and Offshore Wind - with PPA

As shown in Figure 3, the metrics for the onshore with PPA follow a different pattern from those seen previously.

Figure 3: Metrics for onshore with power purchase agreement



As a result of the PPA, the price markup at 5% standard deviation is significantly lower than its equilibrium price of BRL 151 without a PPA, mainly because the PPA allows the onshore wind farm to sell 10% of its energy at a 10% premium (BRL 166.10). A higher standard deviation results in a decrease in the amount of energy sold through PPAs, which results in a higher markup on the unallocated energy. As the standard deviation increases, the price markup values increase as well.

At a 5% standard deviation, the price markup begins at a relatively low value of BRL 71.50. The price markup initially accelerates rapidly as the standard deviation increases. At a 10% standard deviation, it reaches BRL 157.50, which is more than double the price markup at a 5% standard deviation. The rapid acceleration in price markup suggests that the onshore wind farm with PPA is highly sensitive to changes in standard deviation at lower levels of variability.

However, as the standard deviation increases beyond 10%, the rate of increase in the price markup begins to slow down. The price markup increases from BRL 157.50 at a 10% standard deviation to BRL 186.50 at a 15% standard deviation and finally BRL 201.50 at a 20% standard deviation. The deceleration in price markup growth indicates that the onshore wind farm with PPA is less sensitive to standard deviation changes at higher levels of variability.

As the standard deviation increases, the elasticity of the price markup decreases, suggesting that it becomes less sensitive to changes in variability at higher levels. This may be because the PPA provides a certain level of revenue stability which mitigates the impact of increased variability on the economic performance of the wind farm.

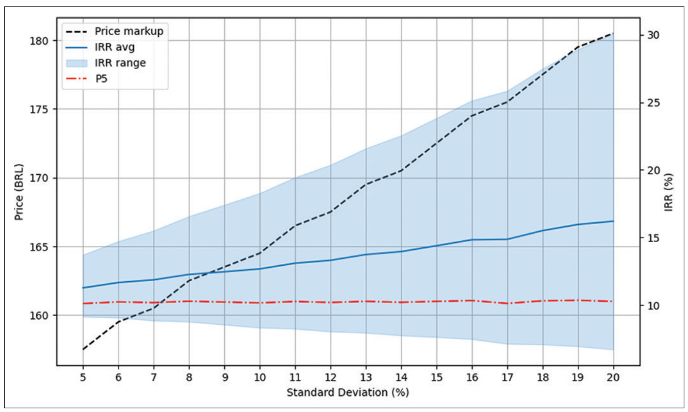
Figure 4 shows the metrics for offshore with PPA. A similar trend is evident in this case, with the markup for the unallocated energy increasing from BRL 78.50 at a 5% standard deviation to BRL 507.50 at a 20% standard deviation.

As with the onshore case, the price markup at a 5% standard deviation for the offshore wind farm (BRL 78.50) is significantly lower than the equilibrium price for the offshore without a PPA (BRL 400), as the PPA allows the offshore wind farm to sell a portion of its energy at a premium.

The price markup for the offshore wind farm with PPA also starts at a low value of BRL 78.50 at a 5% standard deviation, similar to the onshore wind farm with PPA. As the standard deviation increases, the price markup accelerates rapidly. At a 10% standard deviation, the price markup reaches BRL 332.50, which is more than four times the markup at a 5% standard deviation. The rapid acceleration in the price markup suggests that the offshore wind farm with PPA is also highly sensitive to changes in standard deviation at lower levels of variability.

However, as the standard deviation increases beyond 10%, the rate of increase in the price markup remains high but decelerates slightly. As the price markup increases from BRL 332.50 with a 10% standard deviation to BRL 446.50 with a 15% standard deviation, it finally reaches BRL 507.50 with a 20% standard deviation. While price markup growth decelerates, it remains substantial, suggesting that offshore wind farms with PPA continue to be sensitive to changes in standard deviation at higher levels of variability.

Figure 4: Metrics for offshore with power purchase agreement



There is a difference in the elasticity of the price markup for offshore wind farms with PPAs as compared to onshore wind farms with PPAs. At some levels of variability, the offshore wind farm's price markup is more sensitive to changes in standard deviation, whereas at other levels, it is less sensitive. It is possible that this inconsistency is due to the complex nature of offshore wind projects and their increased costs, which may result in a more variable relationship between price markup and standard deviation.

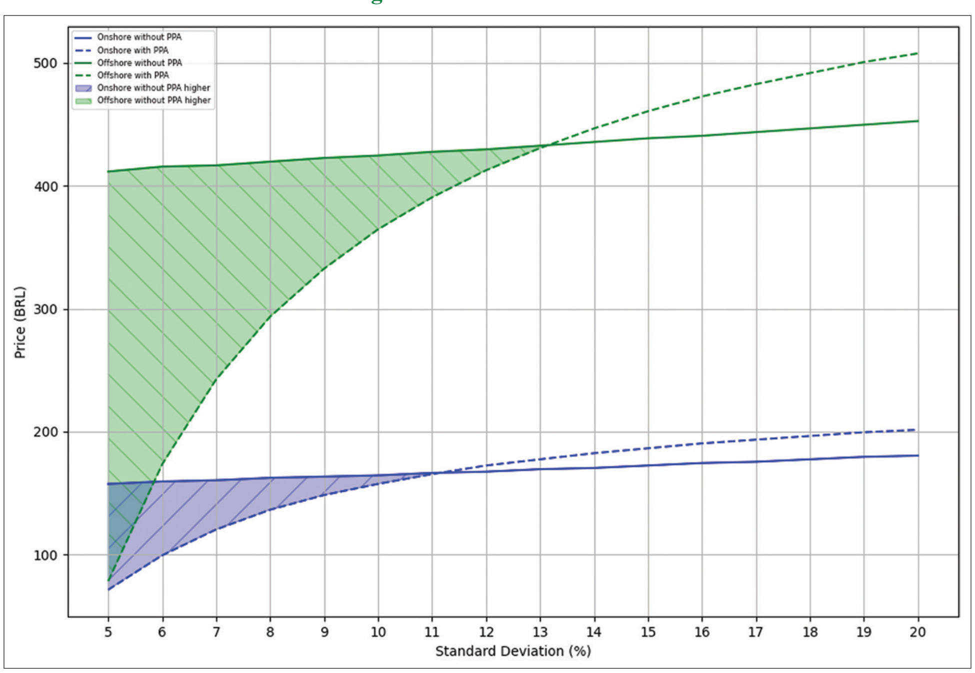
The Figure 5 illustrates the price markup comparison for all cases.

The offshore wind farm's price markup without PPA remains higher than the price markup with PPA until approximately 13% standard deviation, while for the onshore wind farm, this occurs until around 11% standard deviation. This suggests that offshore wind farms can potentially benefit more from PPAs compared to onshore wind farms, especially in scenarios with higher variability in wind energy production.

The difference between the price markup with and without PPA (represented by the shaded areas) is larger for the offshore wind farm compared to the onshore wind farm. This indicates that the presence of a PPA has a more significant impact on reducing the required price markup for offshore wind farms, particularly at lower levels of standard deviation.

As the standard deviation increases beyond the intersection points (11% for onshore and 13% for offshore), the price markup with PPA surpasses the price markup without PPA for both onshore and offshore wind farms. This suggests that at higher levels of wind energy variability, PPAs may not provide sufficient risk mitigation, and wind farms may require higher price markups to ensure financial viability.

Figure 5: Combined metrics



The steeper slope of the offshore wind farm's price markup curves compared to the onshore wind farm's curves indicates that offshore wind farms are more sensitive to changes in wind energy variability. This could be attributed to the higher costs and risks associated with offshore wind development.

The gap between the onshore and offshore price markup curves (both with and without PPA) widens as the standard deviation increases. This suggests that the economic advantages of onshore wind farms over offshore wind farms become more pronounced at higher levels of wind energy variability.

5. CONCLUSION

This study provides insights into the economic performance and price behaviour of onshore and offshore wind farms, both with and without PPAs. The findings highlight the crucial role that PPAs can play in mitigating the risks associated with variable energy production and the importance of considering the unique characteristics of each wind farm type when making investment decisions.

Onshore wind farms without PPAs have slightly higher elasticity values than offshore wind farms without PPAs, suggesting that the price markup for offshore wind farms is less responsive to changes in standard deviation. A comparison of the elasticity values for onshore and offshore wind farms with PPAs revealed inconsistent results. In some instances, the offshore wind farm's price markup is more sensitive to changes in standard deviation, while in others, it is less sensitive.

The inconsistency in the relationship between standard deviation and price markup for offshore wind farms with PPAs may be due to the complex nature and higher costs associated with offshore wind projects. Offshore wind farms are generally more expensive and complex than onshore wind farms. Especially for offshore wind projects, PPAs can provide some degree of revenue stability.

Offshore wind farms without PPAs have slightly lower elasticity values, suggesting that they are less responsive to changes in standard deviation. PPAs could further stabilize the revenue stream and reduce the impact of variability on the project's economic performance by reducing the impact of variability. Although standard deviation and price markup for offshore wind farms with PPAs are inconsistent, the presence of a PPA still provides a level of revenue certainty that is beneficial to these complex projects.

The introduction of PPAs has a profound impact on the price behaviour and economic performance of both onshore and offshore wind farms. Offshore wind farms can potentially benefit more from PPAs compared to onshore wind farms, especially at lower levels of wind energy variability. However, as variability increases, the risk mitigation provided by PPAs may diminish, and both onshore and offshore wind farms may require higher price markups to ensure financial viability.

The findings of this study can contribute to the ongoing debate about the relative merits of onshore and offshore wind energy development. While offshore wind farms have higher costs, this study shows that the introduction of PPAs can make them more financially viable and competitive with onshore wind farms. This insight can help to promote the development of offshore wind energy, which has the potential to play a significant role in the transition to a low-carbon energy system.

REFERENCES

Afshar, K., Ghiasvand, F.S., Bigdeli, N. (2018), Optimal bidding strategy of wind power producers in pay-as-bid power markets. Renewable Energy, 127, 575-586.

Aghamohamadi, M., Mahmoudi, A. (2019), From bidding strategy in smart grid toward integrated bidding strategy in smart multi-energy systems, an adaptive robust solution approach. Energy, 183, 75-91.

Anatolitis, V., Azanbayev, A., Fleck, A.K. (2022), How to design efficient renewable energy auctions? Empirical insights from Europe. Energy Policy, 166, 112982.

Azevêdo, R., Rotela Junior, P., Chicco, G., Aquila, G., Rocha, L.C., Peruchi, R. (2021), Identification and analysis of impact factors on the economic feasibility of wind energy investments. International Journal of Energy Research, 45(3), 3671-3697.

Balaguru, V.S.S., Swaroopan, N.J., Raju, K., Alsharif, M.H., Kim, M.K. (2021), Techno-economic investigation of wind energy potential in selected sites with uncertainty factors. Sustainability, 13(4), 2182.

Cai, H., Jia, X., Feng, J., Li, W., Hsu, Y.M., Lee, J. (2020), Gaussian process regression for numerical wind speed prediction enhancement. Renewable Energy, 146, 2112-2123.

Carvalho, D.B., Pinto, B.L., Guardia, E.C., Marangon Lima, J.W. (2020), Economic impact of anticipations or delays in the completion of power generation projects in the Brazilian energy market. Renewable Energy, 147, 1312-1320.

Chiu, W.Y., Hu, C.W., Chiu, K.Y. (2022), Renewable energy bidding strategies using multiagent Q-learning in double-sided auctions. IEEE Systems Journal, 16(1), 985-996.

Côté, E., Đukan, M., de Brauwer, C.P.S., Wüstenhagen, R. (2022), The price of actor diversity: Measuring project developers' willingness to accept risks in renewable energy auctions. Energy Policy, 163, 112835.

De Assis Tavares, L.F., Shadman, M., de Freitas Assad, L.P., Silva, C., Landau, L., Estefen, S.F. (2020), Assessment of the offshore wind technical potential for the Brazilian Southeast and South regions. Energy, 196, 117097.

Del Río, P., Kiefer, C.P. (2023), Academic research on renewable electricity auctions: Taking stock and looking forward. Energy Policy, 173, 113305.

Dukan, M., Kitzing, L. (2021), The impact of auctions on financing conditions and cost of capital for wind energy projects. Energy Policy, 152, 112197.

Fagandini, P., Dierickx, I. (2023), Computing profit-maximizing bid shading factors in first-price sealed-bid auctions. Computational Economics, 61(3), 1009-1035.

Fanzeres, B., Ahmed, S., Street, A. (2019), Robust strategic bidding in auction-based markets. European Journal of Operational Research, 272(3), 1158-1172.

Farkat Diógenes, J.R., Coelho Rodrigues, J., Farkat Diógenes, M.C., Claro, J. (2020), Overcoming barriers to onshore wind farm implementation in Brazil. Energy Policy, 138, 111165.

Freeman, D.J., Kimbrough, E.O., Reiss, J.P. (2020), Opportunity cost, inattention and the bidder's curse. European Economic Review, 129, 103543.

Gao, X., Chan, K.W., Xia, S., Zhang, X., Zhang, K., Zhou, J. (2021), A multiagent competitive bidding strategy in a pool-based electricity market with price-maker participants of WPPs and EV aggregators. IEEE Transactions on Industrial Informatics, 17(11), 7256-7268.

Global Wind Report. (2023), Available from: https://gwec.net/globalwindreport2023 [Last accessed on 2024 Feb 13].

Jansen, M., Beiter, P., Riepin, I., Müsgens, F., Guajardo-Fajardo, V.J., Staffell, I., Bulder, B., Kitzing, L. (2022), Policy choices and outcomes for offshore wind auctions globally. Energy Policy, 167, 113000.

Kell, N.P., Santibanez-Borda, E., Morstyn, T., Lazakis, I., Pillai, A.C. (2023), Methodology to prepare for UK's offshore wind contract for difference auctions. Applied Energy, 336, 120844.

Kitzing, L., Siddique, M.B., Nygaard, I., Kruger, W. (2022), Worth the wait: How South Africa's renewable energy auctions perform compared to Europe's leading countries. Energy Policy, 166, 112999.

Lozer dos Reis, M.M., Mazetto, B.M., da Silva, E.C.M. (2021), Economic analysis for implantation of an offshore wind farm in the Brazilian coast. Sustainable Energy Technologies and Assessments, 43, 100955.

Martín, H., Coronas, S., Alonso, À., de la Hoz, J., Matas, J. (2020), Renewable energy auction prices: Near subsidy-free? Energies, 13(13), 3383.

Martínez-Ruiz, Y., Manotas-Duque, D.F., Ramírez-Malule, H. (2020), Evaluation of investment projects in photovoltaic solar energy using the dnpv methodology. International Journal of Energy Economics and Policy, 11(1), 180-185.

Matthäus, D. (2020), Designing effective auctions for renewable energy support. Energy Policy, 142, 111462.

Mazzi, N., Kazempour, J., Pinson, P. (2018), Price-taker offering strategy in electricity pay-as-bid markets. IEEE Transactions on Power Systems, 33(2), 2175-2183.

Ministério de Minas e Energia. (2022), Empresa de Pesquisa Energética. Parâmetros de Custos - Geração e Transmissão. Available from: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/publicacoesarquivos/publicacao-607/topico-591/caderno%20de%20par%c3%a2metros%20de%20custos%20-%20pde2031.pdf [Last accessed on 2024 Feb 17].

Ministério de Minas e Energia. (2022), Empresa de Pesquisa Energética. Plano Decenal de Expansão de Energia 2031. Available from: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-2031 [Last accessed on 2024 Feb 17].

Moreno, R., Larrahondo, D. (2020), The first auction of non-conventional renewable energy in Colombia: Results and perspectives. International Journal of Energy Economics and Policy, 11(1), 528-535.

Motamedi Sedeh, O., Ostadi, B. (2020), Optimization of bidding strategy in the day-ahead market by consideration of seasonality trend of the market spot price. Energy Policy, 145, 111740.

Narajewski, M., Ziel, F. (2022), Optimal bidding in hourly and quarter-hourly electricity price auctions: Trading large volumes of power with market impact and transaction costs. Energy Economics, 110, 105974.

Perrelli, A., Sodré, E., Silva, V., Santos, A. (2023), Maximizing returns and minimizing risks in hybrid renewable energy systems: A stochastic discounted cash flow analysis of wind and photovoltaic systems in Brazil. Energies, 16(19), 6833.

Pontes, L., Costa, T., Souza, A., Dantas, N., Vasconcelos, A., Rissi, G., Dias, R., Mohamed, M.A., Siano, P., Marinho, M. (2023), Operational data analysis of a battery energy storage system to support wind energy generation. Energies, 16(3), 1468.

Shojaabadi, S., Galvani, S., Talavat, V. (2022), Wind power offer strategy in day-ahead market considering price bidding strategy for electric vehicle aggregators. Journal of Energy Storage, 51, 104339.

Stephenson, D.G., Brown, A.L. (2021), Playing the field in all-pay auctions. Experimental Economics, 24(2), 489-514.

Stetter, C., Piel, J.H., Hamann, J.F.H., Breitner, M.H. (2020), Competitive and risk-adequate auction bids for onshore wind projects in Germany. Energy Economics, 90, 104849.

Swider, D.J., Weber, C. (2007), Bidding underNprice uncertainty in multi-unit pay-as-bid procurement auctions for power systems reserve. European Journal of Operational Research, 181(3), 1297-1308.

Takano, Y., Ishii, N., Muraki, M. (2018), Determining bid markup and resources allocated to cost estimation in competitive bidding. Automation in Construction, 85, 358-368.

Tan, Z., Liu, S. (2022), The generalized first-and second-price auctions: Overbidding, underbidding, and optimal reserve price. Mathematics, 10(3), 403.

Turkovska, O., Castro, G., Klingler, M., Nitsch, F., Regner, P., Soterroni, A.C., Schmidt, J. (2021), Land-use impacts of Brazilian wind power expansion. Environmental Research Letters, 16(2), 024010.

Wen, H., Ma, J., Gu, J., Yuan, L., Jin, Z. (2022), Sparse variational Gaussian process based day-ahead probabilistic wind power forecasting. IEEE Transactions on Sustainable Energy, 13(2), 957-970.

Yang, Y.C., Chiu, Y.C., Hong, C.Y. (2020), Analysis of cost-benefit and Co_2 emissions of solar energy-intelligent poultry feeding system: Application of NPV and dynamic environmental I-o model. International Journal of Energy Economics and Policy, 10(1), 178-184.

Zhu, L., Li, L., Su, B. (2021), The price-bidding strategy for investors in a renewable auction: An option games-based study. Energy Economics, 100, 105331.