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Development of A Leader–Follower Game Model for Competitive Electricity Pricing in Wind-Based Microgrids with Soft Imbalance Control

Mohammad Amin Maftoon¹, Razieh Keshavarzfar^{1,*} , Narges Norouzi¹

¹ Department of Industrial Engineering, NT.C., Islamic Azad University, Tehran, Iran; mohammadamin.maftoon@iau.ac.ir; r.keshavarzfar@iau.ac.ir; nargesnorouzi@iau.ac.ir.

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Abstract

This study develops an economic model for competitive electricity pricing in wind-based microgrids based on a leader–follower game framework. The decision-making structure consists of a wind energy producer, a microgrid, a Distribution Network Operator (DNO), and end consumers, which interact within a hierarchical framework. To preserve analytical tractability and avoid the complexity caused by difficult constraints, the imbalance between generation and demand is modeled through a soft penalty term in the microgrid's profit function. In addition, the effect of a green incentive is incorporated as a supportive parameter in the microgrid's profit structure. The demand function is defined by considering electricity price, network tariff, greenness level, and wind power generation, while the profit functions of the players are formulated in an integrated manner. The analytical results show that an increase in the imbalance penalty coefficient leads to more conservative pricing behavior, reduces demand, and limits the microgrid's profit. In contrast, strengthening the green incentive reduces cost pressure, enables more competitive pricing, and improves both demand and profitability. The proposed framework can provide a basis for designing pricing mechanisms and economic policy-making in wind-based microgrids.

Keywords: Stackelberg game, Wind-based microgrid, Competitive electricity pricing, Imbalance, Distribution network operator, Green incentive.

1 | Introduction

The increasing penetration of renewable energy resources into modern power systems has fundamentally reshaped the operational, economic, and regulatory architecture of electricity networks. Among renewable technologies, wind power has gained particular importance because of its scalability, relatively mature conversion technology, low marginal operating cost, and expanding contribution to electricity generation portfolios. Within this context, wind-based microgrids have emerged as an effective organizational structure for integrating distributed renewable generation, enhancing local energy autonomy, improving environmental

 Corresponding Author: r.keshavarzfar@iau.ac.ir

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performance, and reducing dependence on fossil-fuel-based generation. However, despite these advantages, the intermittent and uncertain nature of wind generation creates significant challenges for real-time power balancing, demand management, optimal pricing, and economic coordination among market participants. In wind-integrated microgrids, decision-making is not limited to technical dispatch or operational scheduling. Rather, it involves a set of interdependent economic interactions among multiple strategic actors, including wind power producers, microgrid operators, Distribution Network Operators (DNOs), and end consumers. Each actor pursues distinct, sometimes conflicting, objectives. The wind power producer aims to maximize revenue from energy sales; the microgrid operator seeks to optimize electricity procurement and resale decisions while managing green energy integration; the DNO is concerned with network tariffs, transfer charges, and system-level coordination; and consumers aim to minimize electricity payment while maintaining reliable access to energy. Therefore, the pricing problem in wind-based microgrids must be analyzed through a framework capable of capturing both the hierarchical structure of decision-making and the strategic dependence among participants. Game theory provides a powerful analytical foundation for modeling such strategic interactions in decentralized energy systems. In particular, Stackelberg leader–follower games are well suited to electricity market structures in which upstream actors announce prices, tariffs, or incentive signals first, and downstream actors subsequently optimize their decisions in response. This hierarchical decision-making structure has been widely applied to pricing, demand response, distributed generation coordination, storage scheduling, and transactive energy management. Li et al. [1] demonstrated that hierarchical pricing mechanisms in distribution systems can improve economic efficiency by coordinating upstream and downstream pricing decisions. Their work highlights the importance of structured pricing signals in distribution-level energy markets, particularly when multiple actors interact under asymmetric decision authority. The relevance of game-theoretic coordination becomes even more pronounced in microgrids with high renewable penetration. Luo et al. [2] investigated wind-integrated microgrids and showed that game-based coordination mechanisms can improve operational alignment among participants facing wind generation variability. Their findings indicate that strategic interaction models are particularly useful in renewable-based microgrids because they can reflect both market-oriented behavior and uncertainty-driven operational adjustments. Similarly, real-time pricing mechanisms based on Stackelberg games have been employed in virtual power plant environments to regulate demand response and improve the responsiveness of end users to dynamic electricity prices [3]. These studies confirm that price signals can serve not only as economic instruments but also as operational coordination tools in distributed energy systems. Recent research has further extended game-theoretic models to multi-microgrid and integrated energy systems. Hybrid competitive–cooperative game models have been proposed for sustainable multi-microgrid systems in transactive energy environments, incorporating stochastic approaches and environmental considerations [4]. Such models emphasize that future energy systems require pricing and coordination schemes that jointly account for economic efficiency, environmental performance, and uncertainty. In a similar direction, hybrid game-based pricing strategies for shared electro-thermal-hydrogen energy storage have been developed in integrated multi-energy microgrids [5]. These studies show that the inclusion of storage resources and multi-energy carriers adds further complexity to the pricing problem, requiring models that can represent both competition and cooperation among interconnected entities. Low-carbon scheduling and benefit allocation have also been analyzed using combined Stackelberg and bargaining frameworks. For example, Stackelberg–Nash bargaining-based scheduling has been applied to multiple integrated multi-energy systems, showing that hybrid game structures can improve low-carbon operation and distribute economic gains more effectively among participants [6]. This stream of literature demonstrates that advanced game-theoretic models are increasingly used not only for price determination but also for coordinating carbon-reduction objectives, incentive mechanisms, and decentralized decision-making. Moreover, Han et al. [7] proposed a tri-level Stackelberg game for energy storage bidding in multi-microgrid markets and found that dynamic pricing combined with energy storage participation can significantly improve the balance of benefits between microgrid operators and consumers. Their results reinforce the importance of hierarchical game structures in capturing the sequential and strategic nature of energy market decisions. Although the existing literature provides valuable insights into hierarchical pricing, renewable microgrid coordination, shared storage

management, and multi-energy market interactions, several limitations remain. First, many studies focus on two-level or three-level game structures, while the actual operation of wind-based microgrid Supply Chains often involves more than three decision-making layers. In practice, wind power producers, microgrid operators, DNOs, and consumers may each represent distinct decision levels with different objectives and response functions. A simplified two- or three-level structure may therefore fail to fully capture the economic interactions and sequential dependencies that characterize competitive electricity pricing in wind-based microgrids. Second, a substantial portion of the literature relies on hard power-balance constraints to ensure equality between supply and demand. While such constraints are mathematically precise, they may reduce model flexibility and create severe analytical complexity, particularly in systems with intermittent wind power. In wind-based microgrids, deviations between generation and demand are not exceptional events but inherent features of operation. Modeling these deviations exclusively through strict equality constraints can lead to highly constrained formulations that are difficult to solve analytically and may not adequately represent practical operational flexibility. In contrast, the use of a soft penalty mechanism for generation–demand imbalance provides a more realistic and tractable modeling approach. By penalizing deviations rather than prohibiting them outright, the model can preserve operational realism while allowing closed-form analytical solutions. Third, many pricing models treat renewable generation mainly as a technical input or stochastic resource, while insufficient attention is given to policy-driven economic incentives. In practice, the development of renewable microgrids is strongly influenced by green subsidies, environmental incentives, renewable energy credits, and regulatory support mechanisms. Ignoring such policy instruments may limit the explanatory power of pricing models and reduce their relevance for real-world energy markets. Therefore, incorporating a green incentive parameter into the microgrid operator’s profit function can bring the analytical framework closer to practical energy policy conditions and provide insight into how environmental incentives affect pricing behavior, demand, and profitability. To address these gaps, the present study develops an integrated techno-economic model for competitive electricity pricing in wind-based microgrids using a multi-level Stackelberg game framework. The proposed model captures the hierarchical interaction among four key actors: the wind power producer, the microgrid operator, the DNO, and the final consumer. Demand is modeled as a function of electricity price, transmission tariff, greenness level, and wind generation capacity. This formulation allows the model to reflect both economic and environmental determinants of electricity consumption. Furthermore, instead of imposing a hard balance constraint between generation and demand, the model introduces a soft penalty term to control deviations. This approach improves analytical tractability while maintaining a realistic representation of imbalance risks in wind-based microgrids. The main contributions of this research are fourfold: 1) it proposes a four-level leader–follower game structure for analyzing simultaneous economic and operational decisions in a wind-based microgrid supply chain. This structure extends previous two- and three-level models by explicitly representing the sequential interactions among the Wind Producer (WP), microgrid operator, DNO, and consumer, 2) it replaces strict generation–demand balance constraints with a soft penalty mechanism, thereby preserving analytical solvability while capturing the operational implications of wind uncertainty, 3) it incorporates a green incentive parameter into the microgrid operator’s profit function, enabling the model to assess the economic impact of renewable energy support policies, and 4) it derives equilibrium conditions through backward induction and investigates how key parameters influence optimal pricing decisions, demand response, imbalance behavior, and the profit of each participant. From a theoretical perspective, this study contributes to the literature on renewable microgrid pricing by developing a more comprehensive hierarchical game model that integrates economic pricing, operational imbalance management, and green policy incentives. From a practical perspective, the proposed framework can support microgrid operators, distribution utilities, and policymakers in designing pricing schemes and incentive mechanisms that improve both economic efficiency and renewable energy utilization. By explicitly considering the strategic behavior of multiple actors, the model provides a structured basis for understanding how competitive electricity prices emerge in wind-based microgrids and how policy instruments can influence market outcomes. The remainder of this paper is organized as follows. Section 2 presents the mathematical model and the main assumptions of the proposed wind-based microgrid pricing framework. Section 3 derives the equilibrium solution using backward induction and analyzes the optimal

decisions of all players. Section 4 provides sensitivity analysis with respect to key model parameters and evaluates the economic implications of the proposed mechanism. Finally, Section 5 concludes the paper and suggests directions for future research.

2 | Problem Description and Mathematical Modeling

This study develops a four-level wind-based microgrid Supply Chain model involving four strategic decision-makers: The wind power producer, the microgrid operator, the DNO, and the final consumer. The proposed structure reflects a hierarchical electricity pricing mechanism in which decisions are made sequentially based on a leader–follower game framework. The main objective is to determine the optimal wholesale electricity price, retail electricity price, distribution tariff, greenness level, and final electricity demand under a stable Stackelberg equilibrium. In the proposed model, the wind power producer supplies renewable electricity to the microgrid. The microgrid purchases electricity from the WP and resells it to the final consumer while also determining the greenness level of the supplied electricity. The DNO charges a distribution or transmission tariff for delivering electricity through the distribution network. Finally, the consumer determines electricity demand according to the announced electricity price, distribution tariff, greenness level, and available wind generation capacity. Unlike conventional power-balance models that impose strict equality between generation and demand, this study introduces a soft penalty mechanism to manage the mismatch between actual wind generation and electricity demand. This formulation is particularly suitable for wind-based microgrids because wind power output is inherently intermittent and uncertain. By using a penalty term instead of a hard constraint, the model preserves operational flexibility and enables analytical tractability.

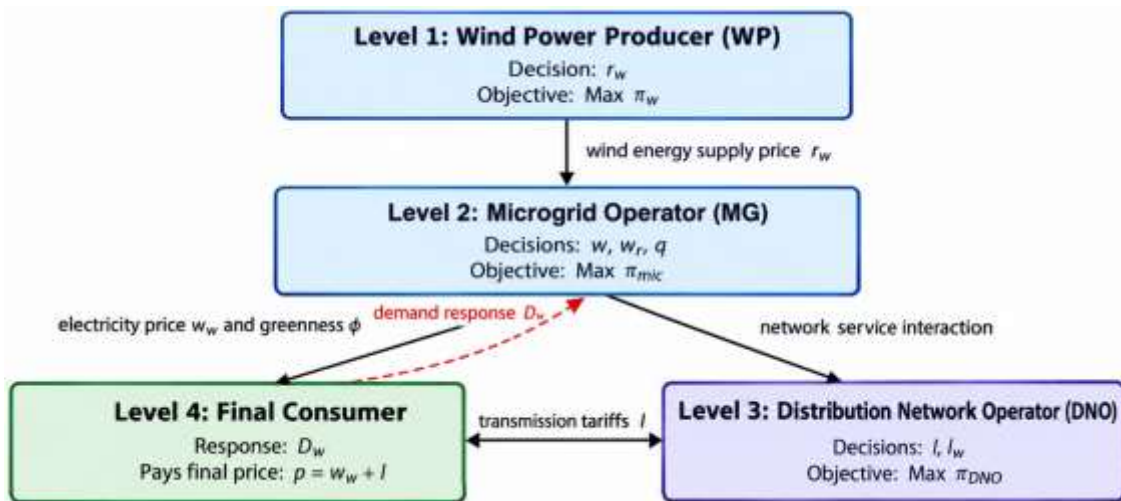


Fig. 1. Hierarchical structure of the proposed four-level Stackelberg game.

Table 1. Model parameters and decision variables.

a	Base demand size of the electricity market
b	Price elasticity of electricity demand
α	Demand elasticity coefficient with respect to the greenness index
η, γ, κ	Technical and efficiency coefficients of wind power generation
v	Wind speed at the site
c	Construction and investment cost per microgrid unit
δ	Variability and intermittency coefficient of the renewable source
q_0	Internal energy consumption within the microgrid boundary
h	Profit earned per unit of internally consumed energy
B	Greenness enhancement cost coefficient
Θ	Soft penalty coefficient for production–demand imbalance
μ, μ_w	Energy transmission cost coefficients in the DNO
ρ	Green incentive rate allocated to the microgrid by the government
c_w	Marginal cost of producing each unit of wind energy for the WP
χ, ψ, s	Coefficients of auxiliary and side revenues in the microgrid system
λ_{gc}	Revenue rate from the sale of green certificates
λ_{rel}	Incentive revenue coefficient from supplying highly reliable and high-quality electricity
c_{om}	Operation and maintenance cost coefficient of the microgrid
σ	Diminishing-return coefficient of the greenness effect on demand
k_{loss}	Loss coefficient of the DNO transmission network
p_{recv}	Recovery revenue rate from thermal losses or wasted energy in the network
p_{ref}	Reference market price used to evaluate deviation and deviation penalties
Φ	Penalty coefficient for deviation of price from the market reference rate
r_w	Wind energy supply price
w_w	Microgrid wholesale electricity price
g	Microgrid greenness effort level
l	Electricity transmission tariff from the DNO to the consumer
l_w	Wind energy transmission tariff to the microgrid
D_w	Final electricity demand of the consumer
p	Final electricity price paid by the consumer
q	Actual wind power generation amount
I	Total investment in the microgrid

2.1 | Demand Function

In the proposed extended model, electricity demand depends not only on the final price paid by the consumer but also on the greenness level of the system and the effective wind-generation component. To capture the diminishing marginal impact of greenness on demand, the model incorporates a concave greenness term with an exponent. Accordingly, the final consumer demand is defined as follows:

$$D_w = a - b(w_w + l) + \alpha(g^\sigma + \eta\gamma\kappa v^3), 0 < \sigma < 1. \quad (1)$$

2.2 | Profit Functions

The wind energy producer generates its profit from the spread between the selling price of wind energy to the microgrid and its marginal production costs.

$$\pi_{wp} = D_w(r_w - c_w). \quad (2)$$

The profit function of the microgrid incorporates revenue streams from green certificate sales and service quality enhancement rewards. Conversely, its cost components include operation and maintenance costs, energy acquisition costs, a price-deviation penalty relative to the reference tariff, and a soft imbalance penalty between generation and demand.

$$\pi_{\text{mic}} = D_w \left(w_w - r_w - l_w + \frac{c}{\delta} + \rho \right) + \lambda_{\text{gc}} g D_w + \lambda_{\text{rel}} g + (\chi + \psi) \gamma \kappa v^3 + (s + h) q_0 - \frac{c_{\text{om}}}{2} g^2 - \frac{\beta}{2} (g - \eta \gamma \kappa v^3)^2 - \frac{\theta}{2} (D_w - \gamma \kappa v^3)^2 - \frac{\Phi}{2} (w_w - p_{\text{ref}})^2. \quad (3)$$

The DNO's profit is defined as the sum of transmission tariff revenue and heat/network loss recovery revenue, minus depreciation costs, technical transmission losses (as a function of total demand), and the penalty for the deviation of the transmission tariff from the market reference rate.

$$\pi_{\text{DNO}} = D_w l + \gamma \kappa v^3 l_w + p_{\text{recv}}(k_{\text{loss}} D_w) - \frac{\mu}{2} l^2 - \frac{\mu_w}{2} l_w^2 - \frac{\Phi}{2} (l - p_{\text{ref}})^2. \quad (4)$$

3 | Model Solution and Findings Analysis

Since the model is structured as a four-level Stackelberg game among the wind energy producer, the microgrid, the DNO, and the end-consumer, the model is solved using the backward induction method. In this approach, the behavior of the lower-level player is determined first, and their optimal response is then substituted into the higher-level problem to ultimately derive the equilibrium of the entire decision-making chain. Within this framework, at the fourth level, the end-consumer determines their demand based on the final electricity price and the level of greenness. At the third level, the DNO, with perfect knowledge of the demand function, selects transmission tariffs to maximize its profit. At the second level, the microgrid determines the wholesale electricity price and the greenness level, accounting for the reactions of the operator and the consumer. Finally, at the first level, the WP determines the wind electricity selling price by anticipating the response of the entire chain. The DNO determines two decision variables, namely l, l_w . To obtain the optimal response, First-Order Conditions (FOCs) are formulated with respect to these two variables. Therefore, the optimal wind transmission tariff is derived from the following relation:

$$\frac{\partial \pi_{\text{DNO}}}{\partial l_w} = 0, \quad (5)$$

$$l_w^* = \frac{\gamma \kappa v^3}{\mu_w}. \quad (6)$$

Moreover, the optimal response of the DNO with respect to the consumer transmission tariff is derived as follows:

$$\frac{\partial \pi_{\text{DNO}}}{\partial l} = 0, \quad (7)$$

$$l^* = \frac{a - b w_w + \alpha(g^\sigma + \eta \gamma \kappa v^3) - b p_{\text{recv}} k_{\text{loss}} + \Phi p_{\text{ref}}}{2b + \mu + \Phi}. \quad (8)$$

The microgrid sets two decision variables, namely the wholesale electricity price and the greenness level.

$$\frac{\partial \pi_{\text{mic}}}{\partial g} = 0, \quad (9)$$

$$g^* = \frac{\lambda_{\text{gc}} g D_w + \lambda_{\text{rel}} + \beta \eta \gamma \kappa v^3 + \alpha \sigma (g^*)^{\sigma-1} \left[w_w - r_w - l_w + \frac{c}{\delta} + \rho + \lambda_{\text{gc}} g^* - \theta (D_w - \gamma \kappa v^3) \right]}{c_{\text{om}} + \beta}. \quad (10)$$

For $\sigma = 1$, and by introducing the following shorthand expressions, we obtain:

$$\Omega = a - b(w_w + l) + \alpha \eta \gamma \kappa v^3, \quad (11)$$

$$\Lambda = w_w - r_w - l_w + \frac{c}{\delta} + \rho, \quad (12)$$

$$g^* = \frac{\lambda_{gc}\Omega + \lambda_{rel} + \beta\eta\gamma\kappa v^3 + \alpha\Lambda - \alpha\theta(\Omega - \gamma\kappa v^3)}{c_{om} + \beta - 2\lambda_{gc} + \alpha^2\theta}, \quad (13)$$

$$\frac{\partial \pi_{mic}}{\partial w_w} = 0, \quad (14)$$

$$w^* = \frac{(1 + b\theta)(A + \alpha g^\sigma) + \Lambda\beta - b\theta\gamma\kappa v^3 - b\lambda_{gc}g + \Phi p_{ref}}{2b + \Phi + b^2\theta}. \quad (15)$$

Similarly, for the wind energy producer, we have:

$$\frac{\partial \pi_{wp}}{\partial r_w} = 0, \quad (16)$$

$$r_w^* = c_w + \frac{D_w}{-\frac{\partial D_w}{\partial r_w}}. \quad (17)$$

To evaluate the model's performance, the main parameters of the wind electricity Supply Chain were first specified, and the values of the decision variables were subsequently obtained by solving the model's equilibrium conditions. It should be emphasized that, in this example, none of the decision variables were assigned arbitrarily; rather, all equilibrium values were determined endogenously through the model solution. Moreover, the parameters were selected such that the profits of all three players are economically viable.

Table 2. Numerical example.

a	200
b	1.5
A	5
σ	0.6
c_w	5
θ	0.02
ϕ	0.1
p_{ref}	25
r_w^*	18.42
w_w	22.15
g^*	15.20
l^*	8.45
l_w^*	6.12
D_w	95.30
π_{wp}	1275.40
π_{mic}	2850.60
π_{DNO}	805.30

To investigate the stability and behavior of the model concerning changes in demand parameters, a sensitivity analysis was conducted for two key parameters, a and b. In this analysis, all other parameters were held constant, while the value of a (and subsequently b) was varied across five different levels. The results indicate that as a increases, all equilibrium variables and player profits also increase. Conversely, an increase in b leads to a reduction in both demand and profits, due to the intensified price sensitivity of the demand. These findings are consistent with the economic logic of the model.

The sensitivity analysis results indicate that, as the base market demand parameter a increases, the equilibrium demand level, decision variables, and the profits of all three players exhibit an upward trend. This upward trend suggests that market expansion strengthens the economic performance of the entire wind power Supply Chain. In contrast, an increase in the price elasticity parameter b reduces equilibrium demand and player profits, because consumers become more sensitive to price changes. Therefore, the obtained results show that the system to examine the effect of the base demand parameter on the equilibrium outcomes, a sensitivity analysis was conducted by varying parameter a across five levels while keeping all other

parameters constant. The corresponding equilibrium results are presented in *Table 3*. Performance is highly dependent on market demand conditions and price elasticity.

Table 3. Sensitivity analysis results with respect to the base demand parameter a .

Level	Parameter a	Equilibrium Demand	WP Profit	Microgrid Profit	DNO Profit
1	150	81.3	1115.4	2550.6	721.3
2	160	88.3	1195.4	2700.6	763.3
3	170	95.3	1275.4	2850.6	805.3
4	180	102.3	1355.4	3000.6	847.3
5	190	109.3	1435.4	3150.6	889.3

As shown in *Table 3*, increasing the base demand parameter a leads to a systematic increase in equilibrium demand, the decision variables, and the profits of the WP, microgrid, and DNO. In particular, the equilibrium demand increases from 81.3 to 109.3, while the profits of the WP, microgrid, and DNO increase from 1115.4 to 1435.4, from 2550.6 to 3150.6, and from 721.3 to 889.3, respectively. These results indicate that an expansion in market size enhances the overall economic performance and profitability of the wind electricity Supply Chain. *Fig. 2* graphically represents changes in player profits resulting from variations in the base demand parameter a .

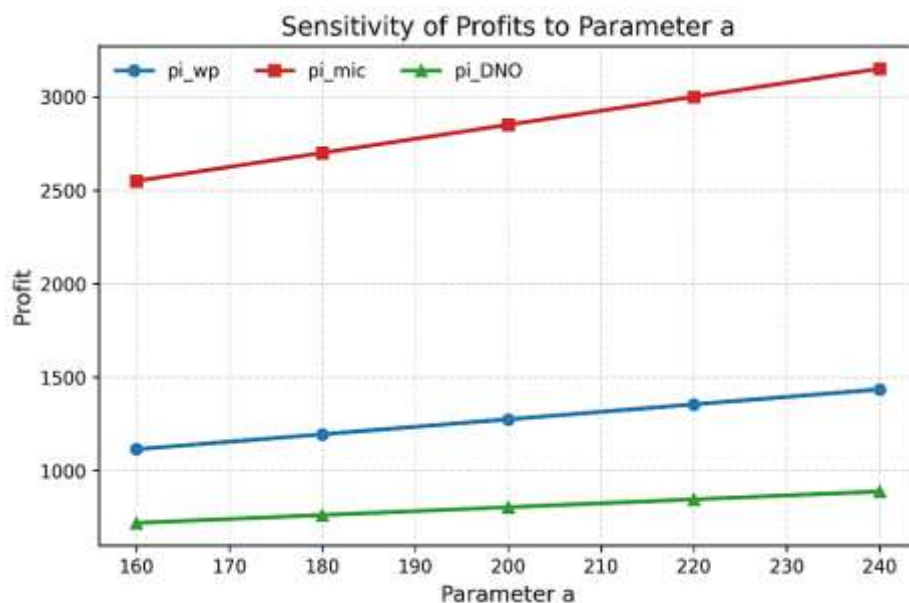


Fig. 2. Sensitivity of player profits to the base demand parameter a .

As illustrated in *Fig. 2*, the profits of the WP, microgrid, and DNO increase monotonically as the base demand parameter a rises. Among the three players, the microgrid obtains the highest profit level throughout the examined range. Overall, the figure confirms that market expansion generates positive economic benefits for all participants in the wind-based electricity Supply Chain. To assess the influence of consumer price sensitivity on the system performance, parameter b was varied across five levels while all other model parameters were held constant. The obtained equilibrium results are summarized in *Table 4*.

Table 4. Sensitivity analysis results with respect to the price elasticity parameter b .

Level	Parameter b	Equilibrium Demand	WP Profit	Microgrid Profit	DNO Profit
1	1.1	102.5	1347.4	2954.6	843.3
2	1.3	98.9	1311.4	2902.6	824.3
3	1.5	95.3	1275.4	2850.6	805.3
4	1.7	91.7	1239.4	2798.6	786.3
5	1.9	88.1	1203.4	2746.6	767.3

Table 4 demonstrates that an increase in the price elasticity parameter b negatively affects equilibrium demand and the profitability of all market participants. Specifically, as b increases from 1.1 to 1.9, equilibrium demand declines from 102.5 to 88.1. Similarly, the profits of the WP, microgrid, and DNO decrease from 1347.4 to

1203.4, from 2954.6 to 2746.6, and from 843.3 to 767.3, respectively. This result is economically intuitive because a higher value of b reflects a stronger consumer reaction to electricity price changes, thereby reducing demand and weakening the economic performance of the supply chain. Fig. 3 depicts the effect of changes in the price elasticity parameter b on the profits of the WP, microgrid, and DNO.

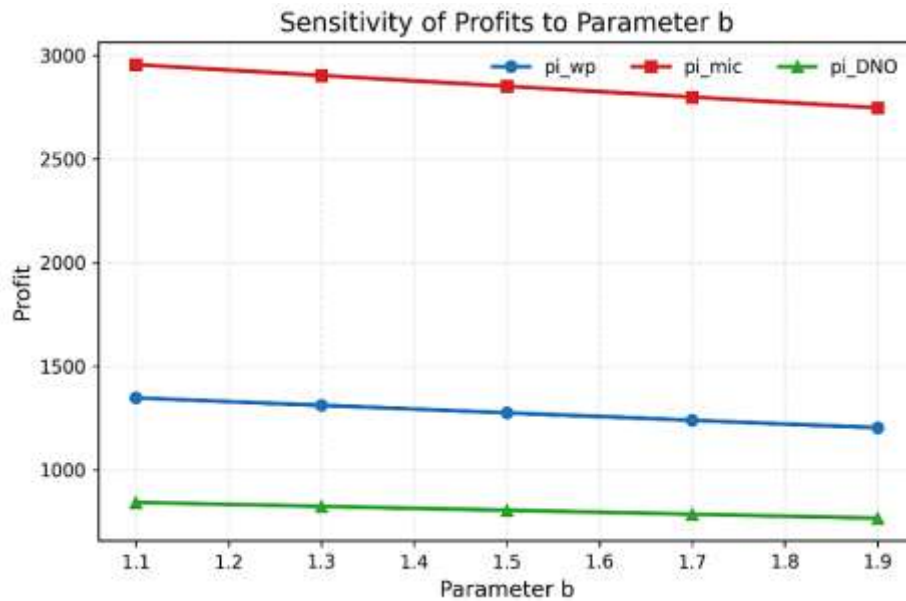


Fig. 3. Sensitivity of player profits to the price elasticity parameter b .

As shown in Fig. 3, the profits of all three players decrease consistently as the price elasticity parameter b increases. This declining pattern indicates that greater consumer price sensitivity adversely affects demand and reduces the profitability of the entire supply chain. Therefore, the results highlight the importance of considering demand elasticity when designing competitive electricity-pricing strategies for wind-based microgrids.

4 | Conclusion

This study successfully established a comprehensive four-level Stackelberg game framework to analyze the strategic interactions within a wind energy supply chain, incorporating the WP, the microgrid, the DNO, and the end consumer. The developed model demonstrates that equilibrium decision variables and profits can be determined endogenously, aligning perfectly with market economic theory while providing a clear picture of how hierarchical decision-making influences system-wide performance. Our findings reveal that the economic viability of the Supply Chain is highly sensitive to market scale; specifically, when the base market demand increased from 150 to 190, the system experienced a robust growth in equilibrium demand from 81.3 to 109.3. This expansion in market volume yielded substantial financial improvements across all stakeholders, with the WP's profit rising from 1115.4 to 1435.4, the microgrid's profit climbing from 2550.6 to 3150.6, and the DNO's earnings increasing from 721.3 to 889.3. These results confirm that scaling the consumer base is a primary lever for enhancing the overall economic performance of wind-based energy systems.

Conversely, the study highlights the risks associated with consumer behavior, particularly regarding price sensitivity. When consumer responsiveness to price changes increased from 1.1 to 1.9, the system faced a contraction in equilibrium demand, which fell from 102.5 to 88.1. This shift inevitably eroded profitability, causing the WP's profit to drop to 1203.4, the microgrid's to 2746.6, and the network operator's to 767.3. These findings provide a vital managerial insight: The success of a wind energy Supply Chain is not merely a function of production capacity but is deeply dependent on how pricing strategies are calibrated against consumer price elasticity. To maintain profitability, stakeholders must therefore shift their focus from raw capacity expansion to demand-side management, optimized tariff design, and the effective alignment of green

incentives. Moving forward, while this deterministic framework offers a solid foundation for understanding current market dynamics, future research should integrate more complex real-world variables, such as the stochastic nature of wind energy intermittency, multi-leader competitive structures, and the implementation of long-term power purchase agreements, to further enhance the predictive accuracy and operational applicability of the model in volatile energy markets.

Authors' Contributions

All aspects of the research and manuscript preparation were carried out by the author. The author has read and approved the final version of the manuscript.

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Data Availability

All data supporting the reported findings in this research paper are provided within the manuscript.

Conflict of Interest

The author declares that they do not have any conflict of interest.

Consent for Publication

The author confirms consent for the publication of this work.

Ethics Approval and Consent to Participate

This article does not contain any studies with human participants performed by the author.

References

- [1] Li, J., Yang, B., Pan, Z., Li, H., Gao, D., & Jiang, L. (2025). Stackelberg-Nash bargaining-based low-carbon scheduling for multiple integrated multi-energy systems. *Energy*, 339, 139024. <https://doi.org/10.1016/j.energy.2025.139024>
- [2] Luo, J., Panchabikesan, K., Lai, K., Olawumi, T. O., Mewomo, M. C., & Liu, Z. (2024). Game-theoretic optimization strategy for maximizing profits to both end-users and suppliers in building rooftop PV-based microgrids. *Energy*, 313, 133715. <https://doi.org/10.1016/j.energy.2024.133715>
- [3] Norouzi, F., & Jadid, S. (2025). Hybrid competitive-cooperative games modeling for sustainable multi-microgrid in transactive energy systems considering stochastic approaches and environmental perspectives. *Energy*, 333, 137412. <https://doi.org/10.1016/j.energy.2025.137412>
- [4] Karimi, H., & Jadid, S. (2021). Modeling of transactive energy in multi-microgrid systems by hybrid of competitive-cooperative games. *Electric Power Systems Research*, 201, 107546. <https://doi.org/10.1016/j.epsr.2021.107546>
- [5] Xie, B., Zhang, L., & Hao, P. (2024). Real-time pricing demand response mechanism of virtual power plant based on stackelberg game. *Chinese Journal of Management Science*, 32(12), 312–322. <https://doi.org/10.16381/j.cnki.issn1003-207x.2023.1944>
- [6] Zhou, H., & Wei, J. (2025). Research on pricing strategy of shared electro-thermal-hydrogen energy storage in integrated energy multi-microgrid based on hybrid game. *Frontiers in Energy Research*, 13, 1602891. <https://doi.org/10.3389/fenrg.2025.1602891>
- [7] Han, Z., Sheng, H., Liu, Y., Liu, S., Wang, S., & Wang, K. (2026). The biddings of energy storage in multi-microgrid market based on Stackelberg game theory. *Energies*, 19(2), 433. <https://doi.org/10.3390/en19020433>