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Unlocking Building Energy Flexibility: Multi-Layered Pricing Framework Design from Distribution-Level to P2P Markets

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The global energy transition toward decarbonization poses substantial challenges to power grid stability, positioning untapped building energy flexibility as a high-value resource for balancing supply and demand. However, unlocking this resource remains economically constrained, as traditional pricing models fail to capture the heterogeneity of flexibility resources and the multi-objective nature of grid interactions. This commentary analyzes the multi-layered pricing framework designed to coordinate strategic interactions across different market participants. By aligning the disparate objectives of distribution system operators (DSOs), virtual power plants (VPPs)/aggregators, and buildings, such a framework can transform building flexibility into a tangible economic asset that enhances grid resilience and operational efficiency.

INTRODUCTION

The global energy landscape is undergoing a paradigm shift, driven by decarbonization and the integration of intermittent renewable energy sources. This transition poses substantial challenges to the stability and reliability of power grids, making the balance between supply and demand a critical issue. The building sector, accounting for 30% of global final energy consumption and 26% of global energy-related emissions, also connects diverse energy resources including onsite generation, electric vehicles, storage, and flexible loads. To deal with the balance issue, the largely untapped building energy flexibility has emerged as a high-value resource for economic dispatch and grid reserve services. Unlocking building energy flexibility becomes essential for ensuring power system resilience and operational efficiency.

However, the transition of buildings from passive consumers to active prosumers has introduced significant complexity into electricity market design. Specifically, the challenge of categorizing grid services as economic goods complicates the modeling of incentives.[1] Consequently, the utilization of building energy flexibility is no longer a technological bottleneck but an economic one. While the physical capabilities of these resources are readily characterized, the pricing mechanisms required to incentivize their deployment remain underexplored. Traditional pricing models, such as flat-rate or simple time-of-use models, fail to capture the heterogeneity of flexibility resources and the multi-objective nature of grid interactions. Therefore, it is essential to design a multi-layered pricing framework (as shown in Figure 1 *Multi-layered flexibility pricing framework in electricity markets*), that coordinates interactions across different market participants to effectively unlock the building energy flexibility.

MULTI-LAYERED PRICING FRAMEWORK

The operational transaction of building energy flexibility is structured into three hierarchical layers, each addressing specific coordination problems between different market participants.

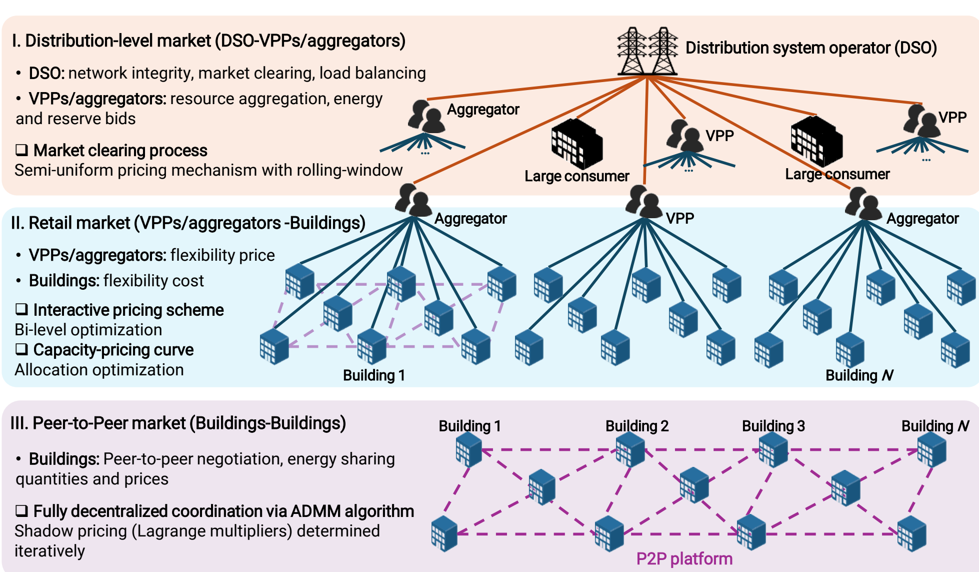

Figure 1. Multi-layered flexibility pricing framework in electricity markets

Layer I. The distribution-level market (DSO-VPPs/aggregators). This layer focuses on flexibility trading between distribution system operator (DSO) and virtual power plants (VPPs) or aggregators. VPPs/aggregators enable small, distributed energy resources to be aggregated into a virtual capacity sufficient for participation in distribution-level markets, generating new revenue streams for asset owners and providing valuable flexibility for the DSO. VPPs/aggregators bid into electricity markets and accept market clearing results and prices determined by the DSO.[2] Subsequently, the DSO decides and submits hourly energy and reserve exchange quantities to the transmission system operator through the root node based on the forecasted wholesale market price.

Layer II. The retail market (VPP/aggregators-buildings). This layer manages the interaction between VPP/aggregators and individual buildings. This interaction can be characterized as a strategic behavior, where incentives are dynamically optimized to align the VPPs/aggregator's financial goals with flexibility costs on buildings, particularly regarding storage opportunity costs and the potential compromise of occupant comfort during flexible dispatch. To address this, a bi-level optimization problem can be modeled: the upper level maximizes the VPP/aggregator's profit, while the lower level minimizes the building users' flexibility costs, thereby explicitly capturing their willingness to participate.

Layer III. The Peer-to-Peer market layer (buildings-buildings). This layer facilitates localized energy trading between heterogeneous smart buildings. Energy sharing is executed via a secure P2P platform that allows buildings within a cluster to communicate electricity quantities and prices and conduct monetary transactions. By utilizing a fully decentralized mechanism, buildings can optimize their schedules in parallel while maintaining privacy. They exchange only limited information, specifically energy sharing quantities and shadow prices with neighbors to achieve market equilibrium and co-optimize energy and reserves.

ANALYSIS AND DISCUSSION

To effectively implement the multi-layered pricing framework, we analyze four specific strategies, evaluating their trade-offs in computational complexity, privacy, and economic efficiency.

Strategy 1: Semi-uniform pricing for aggregated resources in distribution-level market[2]

This strategy proposed a semi-uniform pricing method based on Power-Reserve Flexibility Regions (PRFR) in the market clearing at the distribution system level. Unlike uniform mechanisms, it incorporates non-uniform shadow prices derived from the individual ramping and state-of-charge (SOC) constraints.

It theoretically eliminates the lost opportunity costs common in uniform pricing and incentivizes truthful bidding. It requires VPPs to disclose cost functions to the DSO, which safeguards the privacy of distributed energy resources. However, the iterative nature of calculating PRFR may become computationally intensive for the optimization, especially as the number of distributed energy resources increases.

Strategy 2: Interactive flexibility pricing in the retail market[3]

This strategy models the aggregator-building interaction as a bi-level optimization problem (Stackelberg game). The upper level (aggregator) optimizes incentives, while the lower level (buildings) minimizes costs including thermal/visual discomfort. This scheme quantifies flexibility costs based on physical parameters, such as the predicted mean vote for thermal comfort and horizontal illuminance for visual comfort, allowing users to trade off indoor environmental quality for economic rewards. Comparing simple price signals to an interactive engagement scheme reveals significant efficiency gains.

It explicitly quantifies user willingness, achieving a win-win (e.g., 8.9% profit increase for aggregators and 1.87% cost saving for users). However, bi-level problems generally require efficient solution algorithms like KKT reformulation. This problem can also be solved through distributed optimization to preserve user privacy better than direct control, as only incentives and load signals are exchanged, not raw behavioral data.

Strategy 3: Decentralized P2P energy sharing with virtual storage[4]

This strategy is applied to the P2P market, facilitating horizontal energy trading between buildings while preserving privacy. The pricing is determined via a fully decentralized alternating direction method of multipliers (ADMM) algorithm. Instead of a central authority setting rates, buildings exchange only energy quantities and shadow prices (Lagrange multipliers) to reach market equilibrium. To maximize local flexibility, the thermal inertia of Heating, Ventilation and air-conditioning (HVAC) systems is modeled as virtual energy storage, allowing buildings to price their reserve capacity alongside energy.

This strategy significantly reduces buildings' reliance on the main grid. Simulation results show that P2P energy sharing reduces the total cost for the buildings by 46.9% compared to scenarios without sharing. Additionally, utilizing virtual energy storage for reserve capacity further lowers costs by 49.1% by reducing the need for physical battery degradation and minimizing load shedding. The downside is the communication overhead and iterative convergence can be slow in large-scale networks compared to centralized methods.

Strategy 4: Differentiated capacity-price curve bidding[5]

This strategy bridges the internal building resources and the external market, optimizing how flexibility is aggregated and bidding in the integrated market Layer I and Layer II. Building flexible loads are categorized into three types: lossless transferable loads, lossy transferable loads, as well as lossy reducible loads. Instead of a single price, buildings generate a segmented capacity-price curve (i.e., bidding quantity and price) for each type of building flexibility resources based on their specific modulation costs (e.g., user discomfort) and submit the curve to the VPP. The VPP aggregates these curves and uses a stochastic optimization model to determine the optimal bidding strategy in external distribution-level or wholesale market.

The differentiated capacity-price curve bidding ensures that the building's revenue is positive whether the load flexibility is activated or just in reserve. Compared to average price bidding or highest price bidding strategies, it achieves a more balanced revenue, which ensures that building users obtain reliable incentives while allowing the VPP to maximize its expected revenue across different market clearing price scenarios.

CONCLUSION

The multi-layered pricing framework offers a comprehensive solution by aligning the disparate objectives of DSOs, VPPs/aggregators and building end-users. By implementing targeted pricing mechanisms, ranging from semi-uniform pricing that respects physical aggregation constraints to decentralized P2P clearing that empowers local prosumers, market participants can achieve win-win outcomes of reduced operational costs and enhanced grid stability. The strategies discussed demonstrate that when pricing signals accurately reflect the heterogeneity of flexible resources and the specific constraints of market layers, building energy flexibility transforms from a theoretical concept into a tangible economic asset.

However, realizing this potential requires overcoming systemic challenges beyond algorithmic optimization. Practical implementation is currently hindered by a lack of regulations for dynamic distribution tariffs and P2P trading, which limits the financial viability of these models. Furthermore, the deployment of necessary Advanced Metering Infrastructure and reliable IoT communication introduces high upfront capital expenditures, while the stochastic nature of occupant behavior may degrade theoretical efficiency. Moving forward, bridging the gap between these advanced pricing models and existing regulatory policies will be the decisive step in fully integrating buildings as active, resilient components of the future smart grid.

REFERENCES

1. Lynch MÁ. and Bertsch V. (2025). Lessons from wholesale market success for system service procurement design in high renewable electricity markets. *Nat. Energy* **10**:166−71. DOI:10.1038/s41560-024-01699-0
2. Lin H., Guo Y., Shen X., et al. (2025). A semi-uniform pricing method for VPPs in electricity markets based on power-reserve flexibility regions. *Appl. Energy* **401**:126653. DOI:10.1016/j.apenergy.2025.126653
3. Tang H., Chen Z., Li H., et al. (2025). Risk-aware optimal dispatch of resource aggregators integrating ngboost-based probabilistic renewable forecasting and bi-level building flexibility engagements. *Engineering* **53**:76−89. DOI:10.1016/j.eng.2025.02.009
4. Sun G., Chen X., Zhou Y., et al. (2024). Decentralized distributionally robust energy and reserve co-optimization of smart building clusters with virtual energy storage capability. *Energy Build.* **309**:114040. DOI:10.1016/j.enbuild.2024.114040
5. Qi T., Hui H., Ye C., et al. (2024). Bidding Mechanism Design for Building Virtual Power Plant to Participate in Demand Response Markets. *Auto. Electr. Power Sys.* **48**:14−24. DOI:10.7500/AEPS20240313002

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DECLARATION OF INTERESTS

The authors declare no competing interests.