Guest Editorial
Special Section on Local and Distributed Electricity Markets

I. Introduction

DRIVEN by the goals of clean energy and zero carbon emissions, the power industry is undergoing significant transformations. The rapid growth of diverse distributed energy resources (DERs) at grid edge such as rooftop photovoltaics (PVs) and electric vehicles is transforming the traditional centralized power grid management to a decentralized, bottom-up, and localized control paradigm. Establishing local and distribution-level electricity markets provides an effective solution to managing large amounts of small-scale DERs. New regulations such as the recent FERC Order 2222 in the U.S. open the door to DERs in the wholesale markets. Through coordinating the local and distribution-level markets with the transmission-level wholesale market, the DERs and prosumers can trade energy and flexibility locally with each other and meanwhile provide energy, flexibility and ancillary services to the bulk power grid. During this transition, there are many new technical challenges to address, calling for innovative ideas and interdisciplinary research in this promising direction. Advanced information and communication technologies (ICT) are needed, as a key enabler, for the development and practical implementation of local and distribution electricity markets. Research into local and distribution markets is strongly interdisciplinary, involving the state of the art in power engineering, economics, and digital/information technology. A broad spectrum of contributors from universities, industry, research laboratories and policy makers is sought to develop and present solutions and technologies that will facilitate and advance practical applications and implementations of local and distribution-level electricity markets to uncover the values of DERs.

The guest editorial board received 136 extended abstract submissions to this Special Section and invited 66 of them for full paper submission. The submitted full papers went through the standard review process. After rigorous reviews, 25 papers have been accepted for final publication. These papers are briefly summarized in Section II. This Special Section received widespread contributions from the community. Fig. 1 shows the authorship breakdown by IEEE Regions. It should also be noted that this Special Section encourages collaboration between academia and industry. As a result, 20% of the accepted papers are authored or coauthored by industry experts. An additional 12% of the accepted papers have collaborators from national labs.

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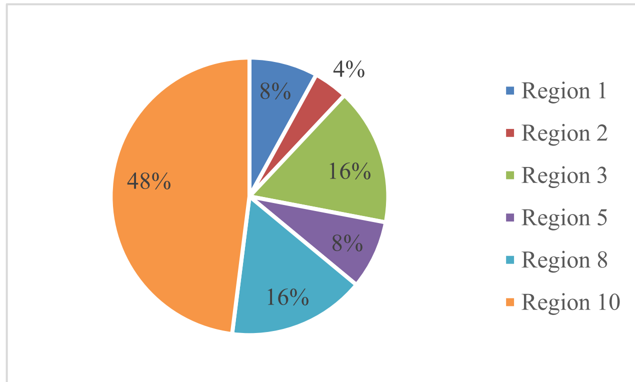

Fig. 1. Authorship of the accepted papers by IEEE Regions.

The scope of the presented papers covers a wide range of topics associated with local and distribution electricity markets:

- Market clearing and pricing in distribution and local electricity markets.
- Coordination and interactions between local, distribution, and wholesale markets, as well as other commodity markets.
- Market participation of DERs and DER aggregators at local, distribution, and transmission levels.
- Grid service trading such as flexibility and reserve in multi-level markets.
- Decentralized peer-to-peer energy and service trading, and distributed ledger technology including blockchain.
- Scalable optimization and control approaches for market integration of large-scale DERs.
- Simulation tool-kit and data analytics to support the implementation of local and distribution markets.

II. Papers in the Special Section

[A1] proposes a hierarchical local electricity market structure with an upper-level market for primary feeders and a lower-level market for secondary feeders, to effectively manage DERs to increase efficiency and resilience of distribution power grids. The lower level market enforces budget, power balance, and flexibility constraints and accounts for costs related to consumers, such as their disutility, flexibility limits, and commitment reliability, while the upper level market enforces grid physics constraints such as power balance and capacity limits, and also minimizes line losses. The proposed hierarchical structure distributes the roles between the two tiers with greater emphasis on grid physics in the upper level and addressing consumer preferences, reliable performance of DERs and monitoring of security breaches in the lower level.

[A2] focuses on detecting load transfers between two meters at the distribution level which could be utilized in the applications to support distribution system and market operation and the system reliability. This paper proposes two methods, a model-free method and a model-based method, inspired by a simple idea: aggregating meters with load transfers offsets the transfers. The proposed methods were evaluated using the data from 428 meters of a U.S. utility company that has 128 load transfers.

[A3] proposes a novel market-clearing model to facilitate energy and flexibility transactions through coordinating the flexibility providers in both transmission and distribution networks. The energy and flexibility market-clearing problem is formulated as a bi-level optimization model that can achieve the optimal allocation of flexibility with the minimum cost through the coordinated operation of TSO and DSOs. The market-clearing results under different DSO scheduling strategies are compared.

[A4] establishes a decentralized market model integrating electricity and carbon emission right (CER) trading for a microgrid. The proposed trading model not only satisfies the demand for transactions but also ensures the constraint of total carbon emissions for the microgrid. Energy storage is introduced to balance loads more economically. Furthermore, by inserting local trackers to global constraints for each node, a scalable fully distributed algorithm is designed to solve the model locally for both global equality and inequality constraints. The proposed algorithm decomposes the arithmetic demand to each user without intermediate agents, which can effectively reduce the cost and ensure the transparency of trading.

[A5] provides a bi-energy trading framework involving electricity and hydrogen. Production of hydrogen via renewable sources is central to the framework described. A traditional pricing (Vickrey) and a hierarchical market structure (Stackelberg game) are embedded into the proposed framework. A number of case studies are used to illustrate the methodology proposed.

[A6] considers an energy hub and provides a bi-level trading framework suitable for distribution systems. At the upper level, the hub operator interacts with the electricity market seeking maximum profit. At the lower level, the different energy subsystems interact rendering a cooperative equilibrium. A number of case studies illustrate the methodology proposed.

[A7] proposes a competitive local energy market where renewable energy aggregators (REAs) can submit bids instead of acting as price takers. A data-driven joint chance-constrained game of REAs is proposed for the optimal bidding problem under the network constraints and the risk-averse chance constraint. Numerical simulations demonstrate that the proposed game model can effectively increase the revenue of reliable players and reduce the overbidding rate of REAs.

[A8] presents a new event-driven peer to peer (P2P) electricity trading framework with distribution network security constraints considered using the generalized fast dual ascent method. Numerical results indicate that the proposed model could guarantee secure operation of the distribution system with P2P energy trading, and the solution method enjoys good convergence performance.

[A9] proposes a novel receding horizon peer-to-peer energy transaction model based on the prediction intervals of renewable energy generation to manage the volatility in the range of a distribution network. A peer-to-peer energy interval matching algorithm is proposed and the responsibilities of undertaking the uncertainty risk from renewable generations are assigned to the counter-part consumers who have been matched with the renewable energy generations. The autonomy energy management problem of each consumer is formulated as a Nash bargaining problem solved by an alternating direction method of multipliers algorithm.

[A10] proposes a fully decentralized dual-loop peer-to-peer energy trading mechanism with voltage regulation capability. In the inner-loop process, the self-interested energy prosumers iteratively achieve optimal energy trading via multi-bilateral negotiation and optimize their reactive power in a decentralized way to satisfy the voltage constraints. If no physically feasible solution is detected, an outer-loop iterative process is activated, where the over-/under-voltage prosumers autonomously adjust their trading quantities to clear the voltage problem.

[A11] proposes a day-ahead optimal bidding model for a retailer with flexible participation of electric vehicles (EVs). The model includes the extended modelling of the investigating period for the bidding, new incentive mechanisms for charging and discharging, and finally the optimal bidding model of a retailer considering the conditional value at risk (CVaR). The proposed model better addresses EVs' temporal distribution, charging and discharging management, and bidding curves compared to the existing bidding models.

[A12] studies the interactions among supplying utility, prosumers and conventional consumers in a distribution market. In such market, each prosumer uses an optimization problem to determine hourly production/consumption and seek maximum profit, and the distribution market operator uses a minimum social-cost problem from which hourly locational marginal prices are derived. Meanwhile, to analyze the economic impacts of an increasing number of prosumers on the basis of the interdependence of producers and operators, an accurate representation of the distribution system operation is provided by using an exact convex relaxation of the AC power flow equations.

[A13] focus on a local energy market where a group of households in a low voltage grid is organized as an energy community. A three-stage management strategy is proposed in this works under the French collective self-consumption framework. In the day-ahead stage, households coordinate with the community manager to minimize the overall energy bills for the next day. Then, the second stage focuses on the mitigation of forecast uncertainties and voltage violation by utilizing the reserve of the local production/storage assets. Finally, the third stage contractually allocates the community energy among the households, in order to ensure fair individual cost reduction and possibly create economic surplus in the community. The proposed community management strategy is evaluated on specific case study of a low voltage grid with 55 households.

[A14] proposes a stochastic bi-level optimization model for the strategic participation of active distribution networks (ADNs) and DERs to provide energy and grid services in wholesale electricity markets, which can capture the interactions between the ADN and the wholesale energy and ancillary service markets. In the upper-level model, the ADN makes optimal decisions on energy and reserve bidding considering the availability, uncertainties, and flexibility of DERs. In the lower-level model, independent system operator performs joint energy and reserve market-clearing to maximize social welfare. The simulation results confirm the effectiveness of the model and the interactions between the ADN and wholesale electricity markets.

[A15] develops a two-stage stochastic bilevel programming model for investors to best allocate battery energy storage systems, where the distribution locational marginal price (DLMP) provides effective market signals for future unit investment. The first stage obtains the optimal siting and sizing of BESSs on a limited budget. The second stage, a bilevel BESS arbitrage model, maximizes the arbitrage revenue in the upper level and clears the distribution market in the lower level. Then, scale reduction strategies for BESS candidate buses and inactive voltage constraints are proposed to reduce the scale of the proposed model. The case studies demonstrate the effectiveness of the DLMP in incentivizing BESS planning and the efficiency of the two proposed scale reduction strategies.

[A16] proposes a model-based system-centric formulation for the coordination of local electricity markets to provide a theoretical optimality benchmark considering the time-coupling operating characteristics of flexible DERs. A model-free prosumer-centric coordination approach for such a local electricity markets is explored to address the practical limitations of model-based system-centric approaches. This is achieved through a new multi-agent deep reinforcement learning method which combines the beneficial properties of the multi-actor-attention-critic and the prioritized experience replay approaches. A real-world case study validates that the proposed local electricity market design successfully encapsulates the economic benefits of both local energy trading and flexibility services provision functions.

[A17] presents an open-source Python-based package named OpenGridGym to seamlessly integrate distribution market simulation with state-of-the-art artificial intelligence decision-making algorithms, with four modules being used for any simulation: a physical grid, a market mechanism, a set of trainable agents and an environment module. Meanwhile, the architecture and design choice for the proposed framework are presented to elaborate on how users interact with OpenGridGym. Case studies are adopted to illustrate the capability and potential of this toolkit in helping researchers address key design and operational questions in distribution electricity markets.

[A18] proposes a fully distributed dynamic transactive control to coordinate distributed energy resources in a distribution system considering physical network constraints based on saddle-point dynamics with a predictive-sensitivity conditioning term is proposed. Meanwhile, a fully distributed continuous-time optimization scheme, which interconnects two levels of decision based on two different timescales into a dynamical system in a single timescale, is proposed to overcome the limitation of the slow convergence rate due to the nested nature and its computational issues. Finally, two simulation cases for a distribution network with distributed energy resources adopted from an IEEE 37-bus test feeder are implemented to validate numerically the proposed approach.

[A19] presents a P2P energy trading method for heterogenous DERs including solar, wind, diesel generator and flexible loads. A reliability credit assignment approach is first developed for customers to differentiate the energy grades considering the heterogeneity in energy supplying reliability of DERs and the consumption preferences of customers. Then the P2P scheme is developed where different types of demands are matched up with their corresponding energy grades, by solving a social welfare optimization problem with the adoption of a fast decentralized pricing algorithm. Another contribution of this paper is to devise a fast solution scheme so that the proposed P2P approach can be applied to large-scale systems. Simulation validations are first conducted on a 69-node system to prove the effectiveness and then tested on the IEEE 8500-node system for scalability demonstration.

[A20] proposes an uncertainty-aware distribution locational marginal pricing (DLMP) approach for day-ahead distribution markets within a transmission and distribution (T&D) coordinated framework. A robust optimization model is proposed to solve the DLMP in coordination with the wholesale market which gets cleared at the transmission level to price energy, reserve, and uncertainty. The resulting scheme can use LMP and DLMP to coordinate the distribution markets with the wholesale markets and the impact of DERs on the wholesale market can be captured to some extent. Another major contribution is that the uncertainty DLMP is introduced to charge the renewable DERs for their uncertainty and reward generators mitigating uncertainties.

[A21] proposes a blockchain based P2P trading architecture to integrate negotiation-based auction and pricing mechanisms in local electricity markets. The negotiation of the volume and price of the P2P trading among prosumers is modeled as a cooperative game, and the interaction between a retailer and its ensemble of prosumers is modeled as a Stackelberg game. The flexibility provision from residential heating systems is incorporated into the energy scheduling of prosumers. Simulation studies prove that the proposed method can reduce 41.24% of average daily electricity costs for individual prosumers.

[A22] proposes and analyzes three different game-theoretical billing methods for the day-ahead scheduling of flexible appliances in a residential community. Each end-user is free to choose its electricity supplier from three different billing methods. Game-theoretical approach is applied so that each prosumer optimizes its day-ahead energy consumption scheduling depending on the applied billing. Numerical analysis shows that the degree of flexibility that characterizes a prosumer has a strong impact on fairness and inefficiency.

[A23] proposes a local electricity market representation method based on umbrella constraints extraction. The authors theoretically derive the closed form of a projection-based feasible region and use it to characterize a constraint set formed by the extreme points of the dual space of the proposed diagnostic methods. A local market is equivalently formulated as a condensed method represented by its temporal-coupled feasible region, in which an umbrella-constraint identification method is developed to reduce the redundant constraints. Simulation studies are conducted on both the 33-bus benchmark system and a 141-node Venezuela system.

[A24] proposes a reactive power market mechanism to unlock the potential of solar energy resources to provide reactive power support. The interaction between the DSO and PV resources is modeled as a bi-level optimization problem. An iterative algorithm is developed to calculate the Nash equilibrium of the proposed market. The market concentration is further quantified to demonstrate its applicability in different power distribution systems.

[A25] introduces an inclusive retail tariff model "NEM X" that captures features of existing net energy metering (NEM) policies. The regulator's rate-setting process is analyzed that determines NEM X parameters such as retail/sell rates, fixed charges, and price differentials in time-of-use tariffs' on and off-peak periods. A stochastic Ramsey pricing program that maximizes social welfare subject to the revenue break-even constraint for the regulated utility is formulated. Performance of several NEM X policies is evaluated using real and synthetic data to illuminate impacts of NEM policy designs on social welfare, cross-subsidies of prosumers by consumers, and payback time of DER investments that affect long-run DER adoptions.

APPENDIX: RELATED ARTICLES

[A1] V. J. Nair, V. Venkataramanan, R. Haider, and A. M. Annaswamy, "A hierarchical local electricity market for a DER-rich grid edge," *IEEE Trans. Smart Grid*, vol. 14, no. 2, pp. 1353–1366, Mar. 2023.

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