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Local Energy Markets: Structural elements and the effects of upscaling

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***Abstract* — Local energy markets (LEM) have attracted a lot of interest in recent years, as an innovative approach for enabling the direct trading of energy between peers within localized areas. The optimal usage of locally produced energy and the cost-effectiveness that can be achieved by avoiding suppliers and aggregators markups are among the benefits the LEM are expected to bring together with the further incentivisation of investments in flexible distributed energy resources (DER) and the reduction of transmission losses. Although the wide adoption of the concept is in its early stage, the interactions of the newly established LEM with the existing market structures that govern the energy and balancing service provision have not been sufficiently studied. This work reviews structural elements of local interaction schemes, introduces coordination styles, and by modelling centrally operated LEM and simulating the wholesale market (WSM) operation, investigates the coupling between prices and focuses on the effects that the different levels of LEM concept adoption may have on WSM. Through a benchmarking case study, scenarios that differ in the mix of DER and the market share of LEM are considered, with the results revealing the effects on WSM outcome and the underlying dependencies in terms of market volume and price trends.**

***Index Terms*-- Transactive energy, Power markets, Distributed energy resources, Electricity Trading**

I. Introduction

Climate change poses a critical threat to both human and environmental health, with rapid shifts in global climate patterns creating substantial adaptation challenges. In response, the Paris Agreement, forged on December 12, 2015, set ambitious targets to curtail greenhouse gas emissions and cap the rise in global temperatures. Power generation stands as the leading contributor to carbon dioxide emissions, yet the path to net zero seems viable with the advent of low-carbon electricity and the growth of renewable energy sources (RES), potentially spearheading the transition to cleaner energy [1, 2, 3]. Despite electricity's status as the second-largest source of energy consumption, increasing from 18 EJ in 1973 to 82 EJ in 2019, a substantial 60% of it was still generated from fossil fuels, especially coal and natural gas, as of 2019 [1]. However, RES, particularly solar PV and wind (both onshore and offshore), are heralded as cost-effective substitutes for fossil fuels, projected to surge by about 95% in global power capacity by 2026 due to enhanced targets and supportive policies [1]. This renewables expansion is poised to exert a downward pressure on energy prices, benefiting even monopolistic markets through the merit-order effect [4, 5, 6].

Distributed Energy Resources (DERs), encompassing technologies like rooftop solar panels, battery storage, and electric vehicles owned by consumers rather than centralized entities, present an efficient and cost-effective means to meet electricity demands, sparking a movement towards electricity market reform [7]. This reform advocates for a bidirectional energy flow that not only delivers power from the grid to consumers but also supports consumer-generated energy and potential trade amongst users. Central to this transition is the Energy Storage Systems (ESS), which provide flexibility and stability to the power system, accommodating the variable supply and demand inherent with increased deployment of RES [8, 9]. With grid-scale battery storage installations reaching approximately 28 GW by the end of 2022, projections suggest that while costs may vary in the short term, a downward trajectory is anticipated by 2030, influenced by market forces, material costs, and technological advancements [10].

Local Energy Markets (LEMs) stand as a beacon for such energy reforms, promising reduced prices and hastened decarbonization by harnessing both large-scale RES and local-level DERs, coupled with ESS. They offer a decentralized energy trading platform, poised to deliver cost savings, reduced supplier dependency, and local economic growth. Yet, the scalability and practical application of LEMs remain under scrutiny. For instance, the Cornwall LEM project's success in emission reduction has yet to be demonstrated on a larger scale due to regulatory barriers that constrain peer-to-peer trading and the engagement of small generators [11, 12]. Current research frequently assumes constant wholesale electricity prices, neglecting how LEMs might influence these costs [13]. As understanding price dynamics in the face of wider LEM adoption is crucial for market participants and policy makers, this work by analysing how an increase in DERs under the LEM framework could affect wholesale electricity prices, aims to identify what the effects of upscaling would be. The potential of ESS in exploiting arbitrage opportunities within the LEM and the wholesale market, is driving economic viability and market effects within the deployed simulation models. As the aim is to unravel the nuanced influence of LEMs upscaling to

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soft- or hard-coupled markets for facilitating more strategic policy development and market structuring for the future, the necessary background around structural elements that influence governance is first developed. The paper is structured as follows; Section II discusses some structural suggestions for integrating distributed assets, reviews the roles of key actors and identifies the main coordination schemes, Section III presents a simulation model for LEM and WSM integration, Section IV presents the key results, whilst the paper concludes in Section V.

II. Structure, Governance, and Integration

With the proliferation of small-scale DERs like solar photovoltaics (PVs), electric vehicles (EVs), and ESS, the notion of localized trading has risen to prominence. LEM have emerged as a transformative approach within the energy sector, allowing for the real-time, localized trading of energy. Under this paradigm, local markets ought to be designed not only to optimize the utilization of locally generated energy but also to enhance grid stability by providing flexibility services like frequency regulation and demand response.

By integrating DERs, LEMs advocate for a decentralized, resilient, and efficient energy system, whilst the proposed shift from traditional systems promises enhanced efficiency and localized control. While LEMs have been the subject of numerous studies and pilots—such as the Cornwall LEM project in the UK and the EMPOWER platform in Europe—they are typically examined within the confines of the distribution grid, often overlooking their potential impact on the wholesale market [14]. Academic studies evaluating the functionality and design of LEMs have seen a marked increase, with transactive energy (TE), community or collective self-consumption (CSC), and peer-to-peer (P2P) energy trading emerging as notable paradigms. Each model presents distinct characteristics in market participation, governance, operations, and outcomes, with an emphasis on integrating end-users into the energy system and exploring diverse operational and business models.

A. Market Structures and the Paradigm Shift with LEMs

Traditional electricity market structures have been predominantly centred around centralized wholesale, with transmission systems focusing on unidirectional flows. LEMs propose a significant deviation from this paradigm, fostering a decentralized approach that aligns generation with local demand. This alignment could lead to more affordable energy solutions, reduced dependency on large suppliers, lower transmission losses, and bolstered local economies. Yet, the current electricity market structures and regulatory frameworks often limit the scope of LEM deployment, particularly concerning the emergence of P2P trading and the inclusion of small-scale generators.

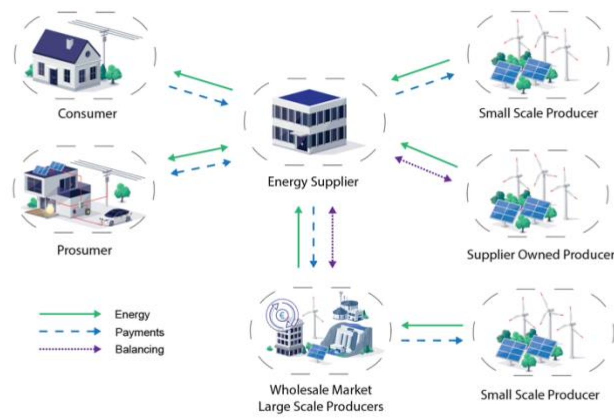

Figure 1. Traditional structure based on the energy supplier business model

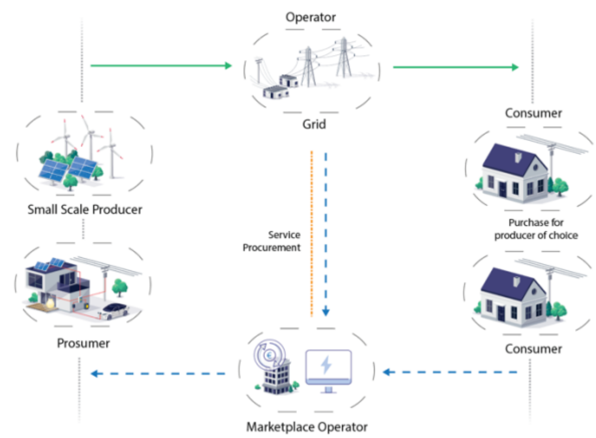

Figure 2. Marketplace structure for facilitating service procurement

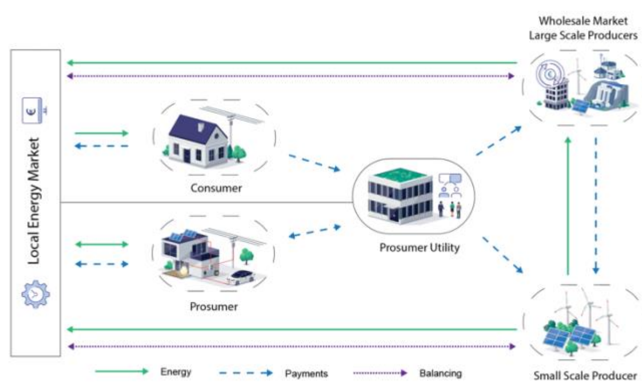

Figure 3. Local Energy Market structure under the transactive paradigm

The coordination within LEMs can range from direct to indirect control mechanisms. Direct control mechanisms often involve a central entity making decisions to optimize system objectives, which can raise privacy and security concerns and

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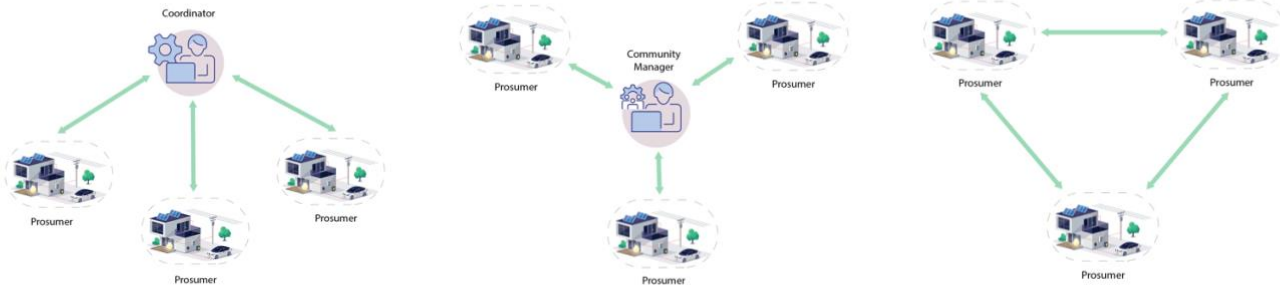

(a) (b) (c)

Figure 4. Coordination styles of LEM

may not be suitable for larger-scale LEMs due to computational intensity and single-point-of-failure risks. Indirect control allows for stakeholder autonomy, where individuals make decisions based on provided information, supporting diverse interests and fostering cooperation for collective benefits. However, realizing the benefits of LEMs requires addressing challenges like regulatory clarity, energy volatility, and grid compatibility. Collaborative efforts, innovative business models [15], and supportive policy frameworks are necessary to overcome these challenges.

Some indicative structures that have been proposed for interaction, service procurement and energy trading at the local level are presented in Figure 1. The traditional structure (Figure 1. that is based on the prosumer-supplier business models [16], focuses on providing reliable and low-cost energy primarily sourced from large-scale dispatchable and a small mix of variable renewable energy sources. This model can be considered the baseline or the 'business as usual' case without specific strategies for managing the increasing variability from variable renewable energy sources (vRES). The marketplace structure (Figure 2. for facilitating service procurement on the other hand, may involve digital platforms that connect producers, prosumers, and consumers directly and pass the market price signal to consumers. This model can be extended to a LEM setting, where transactions can be place-dependent and the contracts can be smart (blockchain). Revenues may be distributed between all the market participants, not only the prosumers. The benefit of local energy markets based on proximity is that they often do not need to pay fees for their unused upstream distribution and transmission networks [17]. The LEM structure provide customers with the ability to maximize the use of their own self-generation assets, such as rooftop solar PV systems. The LEM, closely align with community prosumerism, and can facilitate transactions within community boundaries via peer-to-peer trading on dedicated platforms and empower small-scale energy producers to sell energy directly to consumers. Control processes and IOT developments enable the creation of VPPs that allow excess generation to be sold and enhance the opportunities for realising the stacked value through the combination of multiple revenue streams. Moreover, the service provision is a very important aspect that is directly related to the value proposition and the revenue streams. Together with the aspects of governance, participation and benefit-sharing can extend to the community-oriented setting that has been previously discussed.

B. Actors, Roles and Coordination in LEMs

In the landscape of LEMs, various stakeholders play pivotal roles and create a complex ecosystem that operates through a balance of technical, economic, and social interactions, essential for the effective governance of LEMs. Suppliers bridge the gap between wholesale markets and consumers, stabilizing pricing and supply. Network operators, both Transmission System Operators (TSOs) and Distribution System Operators (DSOs), are critical for managing network constraints and integrating LEMs into the larger energy system. They can also play a more active role in a core product and service pluralistic setting, where network operators can procure flexibility for supporting active network management. Meanwhile, regulators ensure that community objectives such as energy security are met, and prosumers take an active role in managing their energy resources to minimize costs and maximize revenues. Each actor contributes to the LEM's function and governance, supporting a more competitive pricing environment and promoting renewable energy adoption.

Figure 4. presents indicative LEM types for the varying degrees of coordination [18]. In Figure 4(a), the LEM with the individual prosumers who may own solar panels and electric vehicles and contribute through generation, load shifting, and offering flexibility is directly managed by a coordinator, suggesting a more centralized approach to integrating their capabilities into the wider energy system. Figure 4(b) introduces a community manager, indicating a semi-centralized model where a community manager facilitates the interaction among prosumers. This model could blend the benefits of central coordination with the autonomy of prosumers, providing a balance between structured energy management and individual flexibility. Finally, Figure 4(c) represents a peer-to-peer network among prosumers, where they directly interact and exchange energy without a central coordinator. This model emphasizes a decentralized approach to energy sharing, where prosumers negotiate and trade among themselves, potentially leading to more localized and efficient use of energy resources.

III. METHODOLOGY

A. Model Description

The simulation model employed in this study is constructed as a bottom-up modular model with optimization components, aimed at dual objectives: cost minimization within the local

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energy market (LEM) and revenue maximization of flexible assets from the wholesale market (WSM). It presupposes rational economic behaviour where prosumers strive to reduce their electricity expenses, and generators seek to maximize their returns. To provide a 'first-best' approximation of optimal utility from LEM engagement and flexibility options, the model anticipates ideal economic decisions, despite real-world deviations from the strictly rational optimization.

In Figure 5. , an overview of the simulation model is provided, where the two core decision-making modules are interconnected within the simulation framework. The module that simulates the LEM operation captures the options that prosumers have to utilize self-generated electricity, engage in trade within the LEM, or export excess to the grid or activate storage. The WSM module follows a conventional structure where generators and energy storage providers meet with the demand side under a clearing mechanism [19]. The generation bidding sub-module provides bids that have been derived according to the forecast and generation costs, while the ESS sub-module develops a bidding schedule by aiming to optimise actions within the decision-making window.

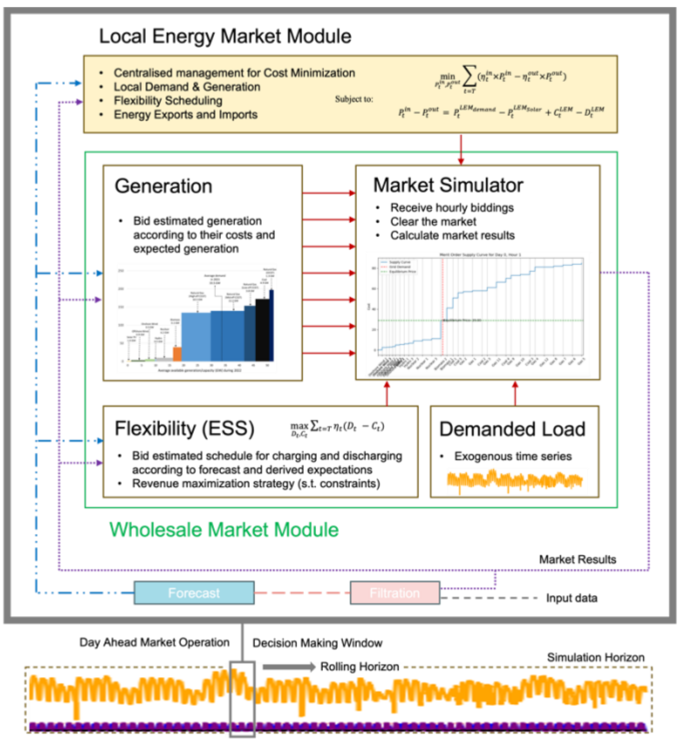

Figure 5. Interconnection of submodels within the simulation framework

B. *Market Clearing and Optimisation*

A day-ahead market system is assumed, with participants submitting bids and offers in anticipation of the following day's hourly prices. The market clearing engine is based on the uniform price single-side auction, which resembles the pay-as-clear scheme in place in the UK.

The constrained optimisation problems that are solved on an hourly basis for a day, take into account the exogenous time series profiles for the load and the vRES generation as well as the technical constraints of flexible assets, such that the energy storage capacity, the charging/discharging power ratings and efficiencies. Balance constraints are also included where appropriate, although there is no independent and explicit consideration of imbalances that may result between the planning that is based on myopic foresight and the actual dispatch, which is considered to take place on the cleared price. The flexibility marketisation strategy is conservative, since it is based on the exploitation of the high intraday price differentials for mitigating issues related to estimation bias.

C. *Market Cases and System Scenarios*

The framework is utilised for quantitatively assessing market cases of system scenarios, where the distributed assets shift their participation from the WSM to the LEM and their capacity increases. These two dimensions of differentiation are captured by the nine case-scenario combinations examined with the first triplet constituting the No LEM case and the next two triplets setting up the Low LEM and High LEM cases. In these variations, the participation in LEM is altered, with the WS-to-LEM ratio being 0:100, 10:90 and 50:50, respectively. Per triplet, the system scenarios span from Low Flex to High Flex, considering the potential of DG increase. This assumption in the development of scenarios follows the positive consequences that the LEM implementation might have in the deployment of DG [20] and given that during the LEMs are in early stages, participants might be provided or encouraged to have more DERs, taking the LEM trial scheme in Cornwall as an example [21]. In this connection, Cases B and C assume the increase in the DG deployment after implementing the LEM will be in proportion to the market shares of the LEM.

IV. Results

In this session, the analysis focuses on the simulation results. It aims to compare the movement of prices with the increase of LEM under the same constraints and under the same system scenario. The simulation considers 2376 points, which correspond to a simulation horizon of 99 days (the initialisation day is dropped) and 24-hour resolution, with any single day constituting a decision-making window.

TABLE I. presents histograms for the price distribution and the first statistical moment as a key indicator. The two dimensions follow the market case and system scenario approach that was presented in Section III.C. A short discussion of those findings follows.

A. *Low Flexibility, Without Increasing DG*

The mean prices follow an increasing trend from the increase in the LEM share. In this system scenario, where there is low flexibility, and the only change in cases is the partial shift of generation, demand and flexibility to local market clearing, there is a transaction volume reduction as the LEM share increases. Given that the shift is symmetric through generation, demand and flexibility, the slight price increase can be attributed to the effect of the flexibility reduction within the WSM. Although the average price is increasing, the hourly prices have the tendency to get closer to the mean. Comparing to the baseline case, where there is no flexibility, the effects of intraday arbitrage can be observed, despite being mild.

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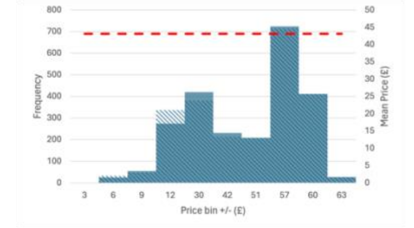
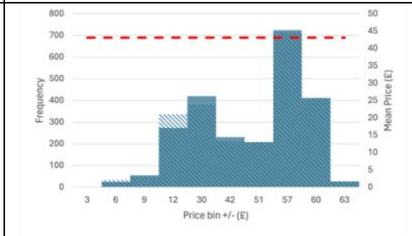
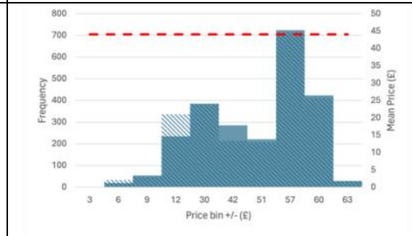
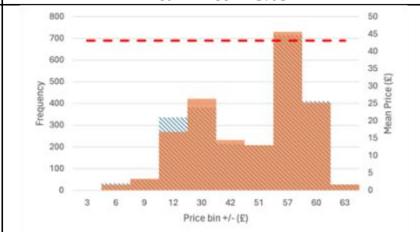
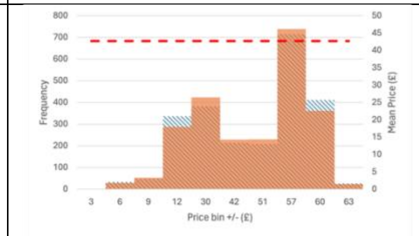
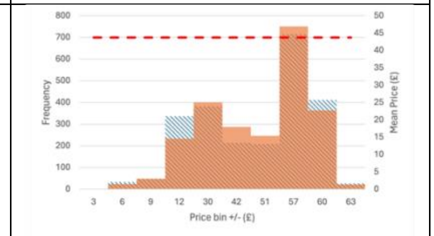
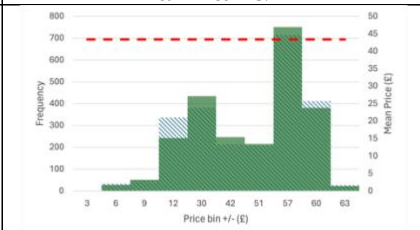
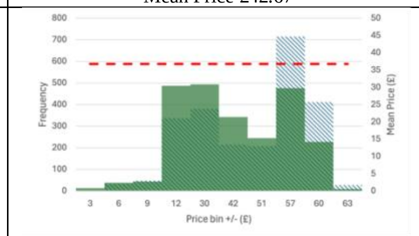
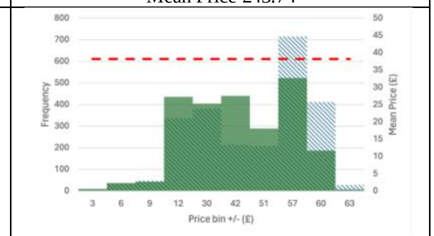
	Low Flex w/o DG Increase	**Low Flex with DG Increase**	**High Flex with DG Increase**
No LEM (0:100)			
	Mean Price £43.09	Mean Price £43.09	Mean Price £44.03
Low LEM (10:90)			
	Mean Price £43.12	Mean Price £42.67	Mean Price £43.74
High LEM (50:50)			
	Mean Price £43.37	Mean Price £36.78	Mean Price £38.16

TABLE I. DISTRIBUTION AND MEAN VALUE OF WSM PRICES

B. *Low Flexibility, With Increasing DG*

The average prices for that system scenario are lower compared to the previous scenario when LEM is introduced as distributed generation increases. Taking the High LEM case as an example, solar generation meets the LEM demand at some hours, and agents trade bilaterally and/or charge the ESS and/or make the surplus available to the WSM. This has a significant impact on the prices, as it frequently shifts the last accepted offer point to a more technologically diverse part of the merit-order curve where flexibility can be better utilized. The merit order effect has helped offset the price increase caused by moving flexibility to the LEM, and the exporting profile of the LEM has become more compatible with the wider system's objectives, so despite the volume decrease, price volatility has been reduced.

C. *High Flexibility, With Increasing DG*

The mean prices for the No LEM case are slightly higher than those of the other system scenarios. These are probably due to the boost in the ESS, which has almost tripled but still has been found insufficient to affect drastically the clearing price. This can be attributed to the exact form of merit order curve, as well as to the conservative market participation strategy of flexibility. Results are significantly different in the case of High LEM, where the increase in DG managed to unlock more arbitrage opportunities. It is worth mentioning that in the High Flexibility scenario, the mean price is found to be higher, which reflects the storage rent, which splits into the charging/discharging losses and the arbitrage gains.

V. CONCLUSIONS

Several structures suitable for the local environment have been considered, and different coordination schemes discussed. The simulation model developed supported the analysis of market cases and system scenarios. Under no additional deployment of DG, the higher market share of the LEM was found to lead to higher average wholesale electricity price. This finding may ally with [22]on the case study of LEM in France and Germany, showing that full integration of flexibility in WSM is more efficient than having the LEM, yet full integration is impossible in reality while LEM could motivate and provide opportunities for the expansion of DG [23] and therefore, it might still be worthwhile to be implemented. When the LEM comes with additional DG, the LEM functions as an efficient market in reducing wholesale electricity prices and concludes that end users can benefit from the LEM and DERs deployments. Previous studies have also suggested that it is more beneficial to implement LEM when the market has a higher self-sufficiency rate than when households are pure consumers served by the grid [24, 25].

Finally, there are significant dependencies on the system scenario, as the capacities and the number of participants in the WSM significantly affect the merit order curve. At the same time, the bid-ask spread between LEM and WSM, which has been ignored, is expected to affect results and the flexibility participation strategy should be more closely examined. All these constitute directions for improvement and future work.

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