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ORIGINAL RESEARCH

Hosting a community-based local electricity market in a residential network

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Abstract

This paper presents the potential of building a local electricity market (LEM) to boost the deployment of the local energy communities, centred around active customers with distributed energy resources (DERs). To conduct a comprehensive and detailed study on different cases with reduced computational burdens, this paper adopts a simplified modelling approach where the market and network model simulations are performed in a cascaded, decoupled fashion. This allows achieving the optimal LEM output for the energy community with different DER assets that are not bounded by the network constraints. The investigation involves quantifying the benefits brought by LEM to energy communities by tapping the flexibility associated with trading inside the energy community. Moreover, it presents the influence of different types of DERs (mainly photovoltaics (PV) and energy storage (ES)) in customers' premises on the outcome of the LEM. The LEM demonstrates successfully the reduction of cost associated with the energy purchased from the energy retailer and maximises the consumption of locally generated clean electricity. Among the studied DER portfolios, the combination of PV and ES solution shows the highest economic potential but deteriorates the voltage profiles and shows high active power loss in the winter month among all the cases examined.

KEYWORDS

local electricity market, low-voltage distribution grid, network performance, peer-to-peer transactions

1 | INTRODUCTION

The rapid share of distributed energy resources (DERs) connected to low-voltage (LV) and medium-voltage (MV) distribution networks (DN) are pushing the transformation of existing energy systems towards a decentralised, decarbonised and digitalised one. A significant portion of DERs is located at or near the end users. To facilitate the integration of DERs, a consumer-centric approach is emphasised in the European Union SET-Plan where consumers are placed at the centre of the energy transition [1]. This has led to significant interest, especially the small-scale residential customers usually connected to the low-voltage distribution network (LVDN). Currently, residential customers have only engagement in the retail electricity market (REM) where customers have a long-term contract with the electricity retailer and the electricity retailer purchases electricity from the wholesale electricity market (WEM) on their behalf [2]. This type of contract specifies the electricity price as fixed-rate or time-of-use prices [3]. The existing REM structure offers very little opportunity to its customers with active participation in the energy transition. The local electricity market (LEM) is an emerging and consumer-centric market approach that enables electricity customers to trade electricity among consumers, producers and prosumers within the regulatory boundary of the energy community. Apart from the empowerment of customers with more active participation, LEM also comes up with multi-benefits, for example, efficient utilisation of DERs, local consumption of locally generated, mostly green electricity, economic savings for local market participants etc. [4].

Nevertheless, the LEM structure, designed around the energy community, prioritises the collective welfare of the energy community over the individual customer. Several studies have been proposed on different community-based energy markets with a focus on the market clearing mechanism, bidding strategy, scalability and convergence of the market. The research found in Ref. [5–9], has been conducted with the focus on different market formulation techniques applied to the LEM to take into account the scalability, convergence, data privacy, prosumer preferences. Market formulation of community LEM considering data privacy of prosumers and a reduced computational burden has been explored in Ref. [5]. A co-operative strategy has been implemented in Ref. [6] for a community of prosumers to maximise the benefits for the community where the decentralised optimisation technique, the alternating direction method of multipliers has been used in the market clearing. A competitive strategy-based (Stackelberg game-theory based) community market has been examined in Ref. [7], which implements a double auction scheme to determine the share of collective energy storage (ES). Both Ref. [8, 9] have proposed a community LEM having provision peer-to-peer(P2P) energy trading based on consumers' preferences where prosumers are taken from different neighbourhoods to form sub-communities, and variable grid cost is included to represent the geographical distance between sub-communities.

Energy storage on customers' premises as one of the key DER assets play a significant role in bringing benefits to the prosumers participating in the LEM. Authors in Ref. [10] present a local energy community trading electricity in P2P transactions and analyse the effect of ES and P2P transactions on the saving of the energy community. A similar study has been performed in Ref. [11] where authors explored the impact of ES flexibility on the LEM for both distributed and centralised storage facilities and presents a comparative analysis. Savings of a residential customer with photovoltaics (PV) and storage can reach up to 28% when customers participate in energy sharing in the community as found in Ref. [12]. The impact of degradation of battery ES due to cyclic operation on market outcome also has been studied in Ref. [13]. Authors in Ref. [14], performed a study on a community-based market with P2P sharing, however, to create a market framework to integrate prosumers in the wholesale market, and day-ahead and intraday market. Usually, the LEM consists of residential customers who are otherwise engaged in the retail market for purchasing electricity. If the LEM is unable to achieve supply-demand matching, it is then facilitated by the electricity retailer through the traditional retail market mechanism. Retail electricity price often is an important factor determining the market-clearing price of the LEM [15] as the buyers' and seller's bids are often constrained by the retail price and feed-in-tariff.

As the LEM is centred around the energy communities where participants are small-scale residential customers, LVDN is of primary focus in the study with its own characteristics. LVDN are traditionally constructed in the 'fit and forget' approach [16] with little or almost no observability and controllability compared to the part of the network with higher voltages. Authors in Ref. [17–19] have looked into the different techniques of incorporating physical network constraints in the study of LEM. Network constraints can be included in the market formulation as AC branch flow equations [20, 21], or linearised DC approximation [22, 23]. This modelling approach is known as optimal power flow and has issues of non-convexity and being computationally burdensome. The non-convex nature of the formulation restricts reaching optimal market outcome and therefore, the full potential of the market and network performance of the LEM at an optimal solution is not fully realised. Another approach is to incorporate certain network constraints, for example, power loss [24–26], the voltage at certain critical nodes [27], in the market formulation instead of full-fledged branch flow equations. However, this approach does not provide an over-arching network performance. An alternative approach to the former methods lies where power flow is performed separately without including it into the LEM formulation. In this case, LEM is cleared without considering any network constraints and power flow is performed to assess network operational performance. Authors in Ref. [28, 29] have developed some examples where the proposed market designs were kept as separate models for the LEM and power flow model working in a decoupled, cascaded manner. This method has several advantages over previous methods as the market outcome of the LEM model is optimal without being bounded by network constraints. This is particularly important in understanding the potential of LEM, its scalability, and initial formation possibility of a self-consumed community without understanding the network complexity if there are any. Then network performance is evaluated for the optimal market outcome. Therefore, the authors of this paper found it a suitable approach for a comprehensive study of impact assessment on LEM by different constituent factors. It is also suitable in regards to the regulatory point of view on eliminating the need for a single entity to be aware of the market and network data [30].

From the review of the studies related to the LEM, authors have observed a lack of a comprehensive, overarching approach where benefits of the community-focussed LEM have been comprehended with the integration of a realistic LV electricity network hosting such a community. The way the different types of residential DER assets impacts the community benefits and network performance are not well-studied. In particular, the operation of ES is subject to change for external price signals such as retail tariff schemes and consequently influences community welfare. To properly understand the value of LEM having different DER assets, the study also has to be performed from hourly resolution to seasonal variation. Furthermore, network performance studies in the literature have not properly focussed on real-life LV, radial DN; the network structure commonly hosting the residential customers, rather uses the synthetic or MV network. As mentioned above, LEM formulation incorporating the branch flow equation or certain network constraints does not provide optimal market outcome and hence, impact assessment of optimal market outcome on the network requires the market model to be decoupled from network constraints and assessed separately to fully understand the impact. There is a clear absence of synergy in analysing different determinant factors, as mentioned above, driving the value of LEM to the energy community in the existing literature. Nevertheless, these synergies are of paramount importance for fostering an energy community from conception to realisation. Therefore, the authors intend to address the above-mentioned research gap holistically. This paper implements the decoupled, cascading LEM and network model [31] presented by the same authors, where the impact of P2P-based LEM trading on the distribution network has been performed for a real-life local energy community located in Ireland. Moreover, this approach will help the relevant authority and stakeholders such as distribution network operators, market operators, aggregators, and regulatory authorities to understand the possible benefits of energy communities and LEM, possible maximum positive/negative impact of DERs and LEM on the distribution network before the implementation of LEM in a real-life environment.

The main contributions of this work are as below:

- Without lessening the performance quality, this paper adopts a simplified modelling approach where the market and network model simulations are performed in a cascaded, decoupled fashion. This accommodates a high volume of data for seasonal study with significantly reduced computational time.
- Demonstrates the value of collective optimisation (at community level) through the local electricity market (LEM) over the self-optimisation of distributed energy resource (DER) assets.
- The impact of the time-of-use (ToU) tariff on the energy storage (ES) performance and thus the impact of ES on the LEM outcome and the distribution network.
- The impact of DERs (active customer with PV only or both PV and ES) on the LEM outcome.
- The extreme cases of self-sufficiency (defined as a share of local generation covering the local consumption) of the energy community due to the seasonal variation in demand and generation are also studied.

The rest of the paper is organised as follows: Market architecture and modelling approaches have been presented in Section 2. Section 3 presents the description of the test scenarios followed by the simulation results and analysis. Finally, conclusions are drawn in Section 4.

2 | METHODOLOGY

2.1 | Market architecture

The LEM envisioned in the paper is focussed on the residential electricity customers, typically under the REM. The proposed LEM provides an alternative for customers to engage in P2P transactions among themselves to reduce dependency on electricity purchases from the REM. The study also investigates how the flexibility emanating from flexible DER assets, to be precise residential ES on customers' premises, stimulates the local trading of electricity and the way it impacts the network operation. However, the market design in this paper does not have the provision of explicit trading of aggregated flexibility services to external parties, for example, local congestion and voltage management for the distribution system operator (DSO), and balancing services for trasmission system operator or balance responsible party etc. Rather, the market is designed to utilise the flexibility to reduce the cost of electricity imported from the grid by the local energy community.

It is logical that LEM participants collectively will not have self-sufficiency across all market periods in the operational time horizon. This necessitates an arrangement to provide excess/deficit energy from the central electricity market to maintain the security of supply. To clarify the case, the deficit/excess energy mentioned above refers to the amount of energy in deficit or surplus, respectively, on customers' premises after local P2P transactions are settled. This work considers that the electricity retailer is responsible to meet the surplus/deficit energy of market participants in business as usual way. Business as usual case refers that the market participants are having contracts with electricity retailers to buy deficit electricity in the retail tariff and sell excess electricity to the grid in the feed-in-tariff. Apart from the electricity retailer and electricity customers, there are other key actors identified in the proposed framework: LEM operator (LEMO) and DSO. The role of LEMO involves managing the P2P transactions among the market participants to reach the goal of the LEM. Market participants in the LEM are the electricity end users: producers, prosumers and consumers. The role of the DSO in the LEM arises from the nature of the market product itself, the electricity that requires to be transported through the physical electrical network, which has its own technical constraints. Maintaining network integrity is therefore essential throughout the LEM operation. The DSO ensures that the P2P transactions in the local market operation is adhering to the technical constraints of the network. Figure 1 illustrates a schematic diagram of the LEM considered in the study.

The LEMO controls the P2P transactions based on the forecasted generation and consumption profiles along with status and characteristics of DER assets, for example, state of charge of ES, maximum charging/discharging limits etc. Local electricity market is considered to have interaction with REM only and no direct involvement with the WEM. This implies the pricing of electricity purchased or sold to the grid by LEM participants, is the usual retail tariff or feed-in-tariff with P2P transaction price inside the local market, which are often capped by retail pricing to boost the local market. Note that such market design ensures that the uncertainty of the market-clearing price of the day-ahead market or intraday market does not affect the LEM clearing price. This assumption is reasonable for electricity end users in LVDN as currently, they interact with the REM only and the proposed LEM is based on the current scenario.

2.2 | Modelling approach

The modelling approach used in the paper is outlined in Figure 2. It has two stages: the first stage is the LEM model as described in the market model subsection of Section 2.2 and the later stage is the network model capturing distribution network hosting the LEM. MOSEK [32] is used as an optimisation solver to solve the linear multi-period optimisation problem of the LEM model developed in the MATLAB environment using the open-source optimisation modelling language, YALMIP [33]. The open-source grid simulator, OpenDSS is used to perform time-series simulation of the complex, unbalanced, 3-phase distribution network [34]. MATLAB has been used in the pre- and post-processing of the data and result presentation. The simulation has been performed in a cascaded fashion and both stages provide the necessary output for the study. At first, the LEM model takes an input dataset consisting of generation and consumption profiles of each LEM participant, the retail tariff and other necessary data such as the specification of key DER assets modelled in the LEM, for example, ES, PV generation. The local electricity market model generates a range of dispatches as its output, for example, grid import and export of individual LEM participants, storage charging, discharging and state-of-charge profiles, P2P exchange profiles etc. Subsequently, using the dispatches generated from the LEM model, a power injection profile is created, which is then used by the LVDN model to perform a 3-phase time-series simulation. The LVDN model also requires the dataset necessary to create the physical structure of the distribution network. This dataset comprises network topology and characteristics of network assets: lines, transformers, capacitor banks, voltage regulators etc.

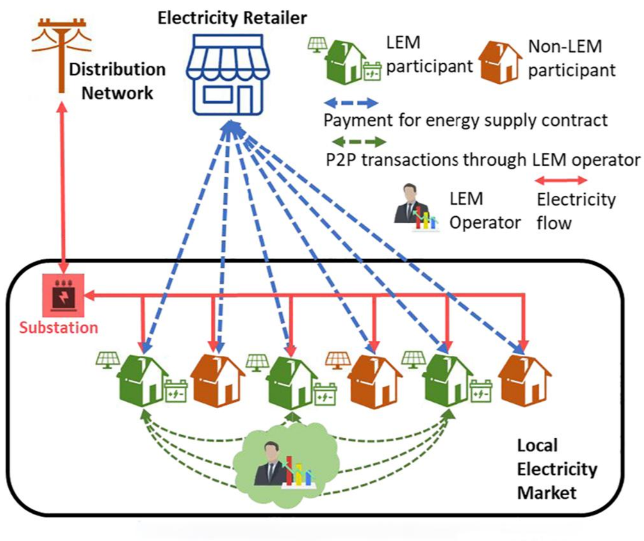

FIGURE 1 Local electricity market (LEM) architecture

2.2.1 | Market model

The primary goal of the LEM is to minimise the cost of procuring electricity and maximise the revenue from exported electricity to the grid under the REM. A linear multi-period optimisation model has been formulated to describe the LEM framework. The objective function of the problem is given by Equation (1),

$$\underset{P_{p,t}^{\mathrm{Im}},\ P_{p,t}^{\mathrm{Ex}}}{\mathrm{Min}} \sum_{t} \left(\sum_{p} \lambda_t^{\mathrm{Im}} P_{p,t}^{\mathrm{Im}} - \sum_{p} \lambda_t^{\mathrm{Ex}} P_{p,t}^{\mathrm{Ex}} \right) \Delta t \tag{1}$$

The first term of the objective function represents the cost function related to buying electricity from the retailer. As the market participants buy electricity from the REM, the price of electricity is the time-of-use tariff offered by the retailer as part of the contract. The second term refers to the revenue function denoting the export of electricity to the grid at a feed-in-tariff rate.

The objective function is subjected to several constraints. Power balance constraints for each market participant needs to be respected for each trading period. This constraint ensures that the summation of injected power in terms of grid import, purchased electricity through P2P transactions from other market participants, ES discharge and self-generated power (if available) must satisfy the load, ES charging, sold electricity in P2P transactions to others and grid export.

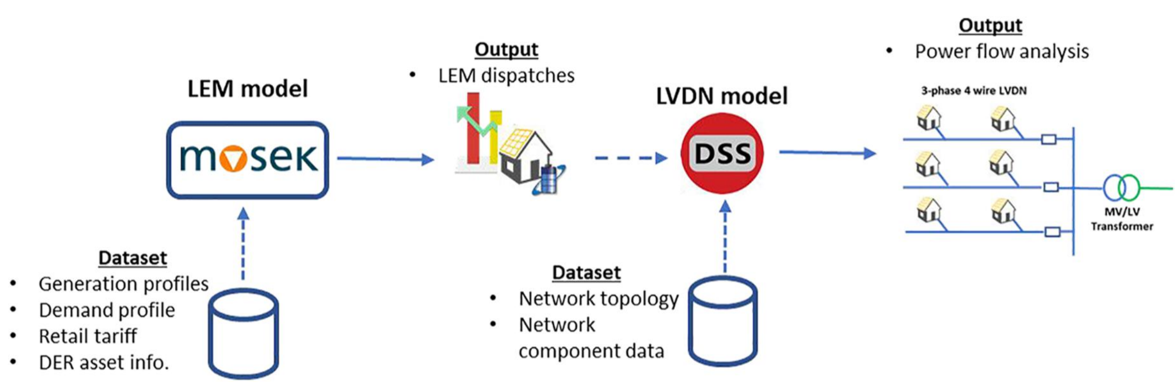

FIGURE 2 Overview of the modelling approach

$$P_{p,t}^{\mathrm{Im}} + \sum_{q \neq p} P_{q \to p,t}^{\mathrm{P2P\ \ buy}} + P_{p,t}^{\mathrm{dis}} + P_{p,t}^{\mathrm{gen}} = P_{p,t}^{\mathrm{Ex}} + \sum_{q \neq p} P_{p \to q,t}^{\mathrm{P2P\ \ sell}} + P_{p,t}^{\mathrm{ch}} + P_{p,t}^{\mathrm{dem}} \tag{2}$$

The latter constraint is more focussed on the balance constraint on P2P transactions inside LEM. This constraint guarantees that total electricity purchased through P2P transactions should be equal to electricity sold in P2P transactions at each trading period.

$$\sum_{p} \sum_{q \neq p} P_{q \to p,t}^{\mathrm{P2P\ \ buy}} = \sum_{p} \sum_{q \neq p} P_{p \to q,t}^{\mathrm{P2P\ \ sell}} \tag{3}$$

Distributed energy resource assets are also required to take into account in the modelling, especially, the assets that are flexible and play a significant role in the outcome of the market operation. Energy storage is one of such key DER assets and is considered here to study their impact on the market outcome. The charging power and the discharging power of the ES system is limited by the inverter size. The upper and lower limit of state-of-energy is bounded by ES capacity.

$$P_{p,t}^{\mathrm{ch}} \leq P_{p}^{\mathrm{ch,max}} \quad ; \quad P_{p,t}^{\mathrm{dis}} \leq P_{p}^{\mathrm{dis,max}} \tag{4}$$

$$\underline{E_p} \leq E_{p,t} \leq \overline{E_p} \tag{5}$$

A simplified linear formulation is used to model ES. It is assumed that the charging/discharging power is constant during the trading period and the state-of-energy of the ES is governed by,

$$E_{p,t} = E_{p,t-1} + \eta_p^{\mathrm{ch}} P_{p,t}^{\mathrm{ch}} \Delta t - P_{p,t}^{\mathrm{dis}} \left(\frac{1}{\eta_p^{\mathrm{dis}}} \right) \Delta t \tag{6}$$

2.2.2 | Network model

After receiving the outcome of the LEM, it is important to assess the impact of the market outcome on the distribution network hosting the market participants. It is a crucial phase to evaluate the network integrity after LEM implementation and requires before the large-scale roll-out of the LEM concept. Therefore, modelling of LVDN is required to conduct power flow simulation on each trading period of the market outcome horizon. Power flow simulation examines the feasibility of local market trading from the network perspective. It implies that all network constraints, for example, line limits, bus voltage, transformer loading etc., are respected. The electricity customers may be LEM participants or non-market participants. For market participants, the load node profiles are created from net injection profiles, calculated by,

$$P_{p,t}^{\mathrm{inj}} = P_{p,t}^{\mathrm{Im}} + \sum_{q \neq p} P_{q \to p,t}^{\mathrm{P2P\ \ buy}} - P_{p,t}^{\mathrm{Ex}} - \sum_{q \neq p} P_{p \to q,t}^{\mathrm{P2P\ \ sell}} \tag{7}$$

Hence, the load node profile is the net profile calculated from the difference of the sum of the active power imported to the node and the sum of the active power exported from the node. The operation of the energy storage is considered taking place behind the meter and therefore not included in Equation (7). The rest of the load node profiles connecting non-market participants are typical consumption profiles. The power flow model requires not only active power profiles but the reactive power profiles as well, although the LEM model only deals with active power profiles. The reactive power profile is obtained from the active power profile considering a constant power factor. There are different power flow solution methods that exist for the distribution network model [35]. However, the power flow solution method used in the model is the default solution algorithm in the OpenDSS simulator [34]. The real-life distribution network used in the study is one of the IEEE standard distribution test feeders and OpenDSS has been successfully used to yield acceptable power flow results for the test feeder [35].

3 | CASE STUDY

3.1 | Test scenario descriptions

The case study is based on real-life measurements, collected from smart homes located in the Dingle Peninsula in Ireland [36]. Each of the homes is equipped with a roof-top PV panel of capacity between 2 and 2.2 KWp and residential ES of capacity of a 10 kWh/3.3 kW peak. A lithium-ion-based battery system has been used as ES. The efficiency of the ES is assumed to be independent of the state-of-charge level and constant throughout the charging and discharging cycle. The degradation model of the ES has not been considered here for this short-term study. Both charging and discharging efficiency are 95%. The measurement devices installed on those smart homes collect the solar PV production and consumption profile (without ES) of the homes separately. To understand the seasonal impact, the case study has been carried out on measurements of 2 months: January and June 2020, representative of winter and summer months respectively. The two representative months have been chosen based on the self-sufficiency metric of the community of 55 smart homes. Self-sufficiency has been defined as the ratio of aggregated PV generation and aggregated demand of the community across the analysed time horizon and expressed as a percentage.

$$\text{Self-sufficiency} \quad (\text{in} \quad \%) = \frac{\sum_t \sum_p \boldsymbol{P}_{\boldsymbol{p,t}}^{\mathbf{gen}}}{\sum_t \sum_p \boldsymbol{P}_{\boldsymbol{p,t}}^{\mathbf{dem}}} \times 100 \tag{8}$$

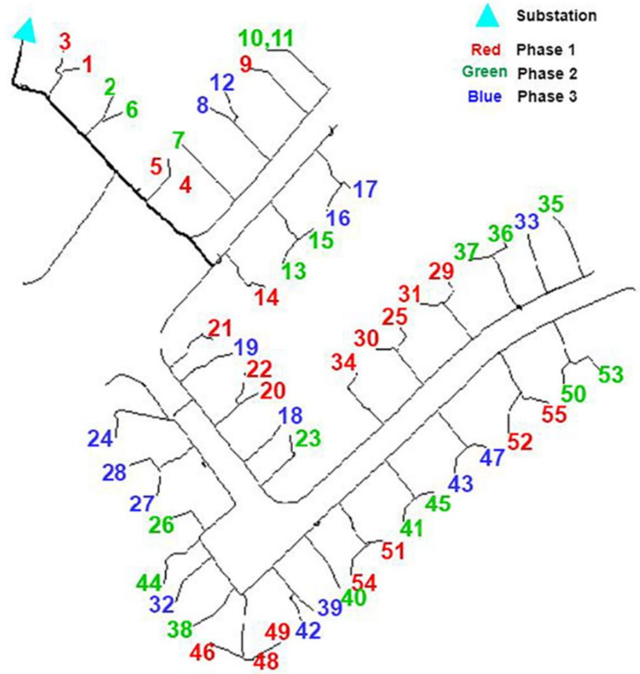

FIGURE 3 Schematic diagram of IEEE LVDN test system identifying customer nodes. LVDN, low-voltage distribution network

Based on the real-life measured data, the self-sufficiency of January and June has been calculated as 12.61% and 62.49%, respectively, which represents opposite extremes for the year 2020. Therefore, these months have been taken as representative months of the winter and summer, respectively.

All those smart houses have been considered as market participants of the LEM and market simulation is performed based on these measured datasets. The ES operation is based on the market optimisation algorithm. As discussed in 2.1, the proposed LEM depends upon the existing REM pricing scheme in Ireland, which is static time-of-use pricing. The day–night retail pricing comprises wholesale energy cost, supplier's cost, grid tariff and government taxes and levies [37]. In 2020, domestic consumers in Ireland with day–night pricing were charged 20.07 c€/KWhr and 9.91 c€/KWhr, respectively. The consumption profiles of the smart homes used in the study were subjected to the day–night pricing scheme. Smart homes are remunerated at a fixed feed-in-tariff of 9 c€/KWhr. Trading also happens in hourly resolution in the LEM model. The LEM modelling approach is deterministic. It assumed the generation and consumption profiles as perfect forecast, although being aware of uncertainty associated with such profiles.

To understand the impact of the LEM on LVDN, an IEEE European LV test feeder is taken as a test network, which is a

TABLE 1 Descriptions of different cases to be analysed along with notations

Case	Notation	Description
Base scenario	*Base-PV*	This is the reference case where each of the homes is equipped with roof-top PV only and the generated electricity from PV is utilised to serve real-time customer's demand. Any surplus or deficit electricity is exchanged with the retailer in the feed-in or time-of-use tariff, respectively.
Self-optimisation with PV and ES	*SO-PV + ES*	The residential ES and roof-top PV are utilised by the home energy management systems of the smart homes to self-optimise the operation of ES to minimise the cost of buying electricity from the grid. This is the business-as-usual scenario where no LEM exists, that is, electricity customers are not involved in P2P trading among themselves.
LEM with PV only	*LEM-PV*	This scenario allows the customers to engage in the trading of electricity based on the LEM approach described in Section 2.2. Each of the customers participating in the LEM only owns roof-top PV.
LEM with PV and ES	*LEM-PV + ES*	Instead of self-optimisation, this case allows the customers to participate in LEM with their roof-top PV and ES assets.

TABLE 2 Comparative analysis among different cases

	Summer				Winter			
	Base-PV	**SO-PV + ES**	**LEM-PV**	**LEM-PV + ES**	**Base-PV**	**SO-PV + ES**	**LEM-PV**	**LEM-PV + ES**
Collective net energy cost (€)	1449	799	1278 (−11.8%)[a]	732 (−8.37%)[b]	3882	2831	3804 (−2%)[a]	2457 (−13.2%)[b]
Grid supply (kWhr)	11,798	9002	10,210	7455	23,398	23,654	22,696	23,973
Grid feed-in (kWhr)	5022	1492	3434 (−31.6%)[a]	67 (−95.5%)[b]	1022	41	321 (−68.6%)[a]	0 (−100%)[b]
P2P transaction (kWhr)	0	0	1588	1934	0	0	701	4126
Cost of grid supply (€)	1901	933	1587	738	3974	2835	3833	2457
Revenue from grid feed-in (€)	452	134	309	6	92	4	29	0

[a]In comparison with Base-PV case.

[b]In comparison with SO-PV + ES case.

radial, 3-phase distribution feeder having typical European network topology supplying LV, residential customers [38]. The test feeder is supplied by an 11 KV/0.416 KV substation having a capacity of 200 KVA and a delta/grounded-wye connection. The test feeder consists of 906 buses and 55 customer connection points for single-phase residential customers. All of the 55 customers are LEM participants located at different connection points. In the power flow simulation, the connection point at the MV/LV substation is taken as a slack bus with the voltage fixed at 1.0 p.u. In alignment with the temporal resolution of the LEM model, the power flow has also been conducted on hourly resolution. Figure 3 shows the schematic diagram of LVDN under study along with the placement of the customers at different connection nodes.

3.2 | Simulation results

The extensive simulation studies are carried out implementing four different cases. All of the four cases, as elaborated in Table 1, have been investigated for both summer and winter representative months. Customer having roof-top PV only without a home energy management system and with no access LEM is considered as the base case. The other three cases are organised based on the combination of customers' DER assets, self-optimisation and access to LEM.

The objective of the cases is to observe the impact of residential DERs on LEM outcomes and also on network performance. For each of the cases, the portfolio of the DER assets will be homogenous among LEM participants, for example, all the LEM participants will have the same type of DER assets under each case. The consumption and the generation profiles of the smart homes have been assumed consistent across all the cases of Section 3.1.

Table 2 presents the aggregated result of all four cases for the entire month of January and June 2020. The result indicates that the introduction of LEM has benefitted the community in reducing their cost of electricity due to the energy exchange (termed as collective net energy cost in Table 2) with the grid (any energy flow through the distribution transformer from a higher voltage grid is considered to be procured from retailer simplistically) for each of the cases. Collective net energy cost is evaluated from Equation (1) and is defined as the net cost of energy exchange of the energy community with the grid (cost of grid supply minus the revenue from grid feed-in). For the LEM-PV + ES case, the winter month has seen the highest benefit as the cost reduced by 13.2% with the introduction of LEM and for only the LEM-PV case, the summer month has seen the highest savings of 11.8%. The result indicates that the role of ES bringing benefit to the community appears crucial for the LEM-PV + ES case in the winter month. The ability of the ES storing electricity in low price hours to cover the demand in the high price hours (energy arbitrage), has been the primal contributor of the savings in the winter experiencing low self-sufficiency due to low PV generation and high demand. The local electricity market extends the possibility of energy arbitrage, as it enables the LEM participants to exchange electricity among each other, thus charging ES at low price hours to sell their peers at high price hours. Numerical figures in grid supply, grid feed-in and P2P transactions second the findings. In the case of LEM-PV, the summer month has shown the highest benefit with LEM facilitating the P2P

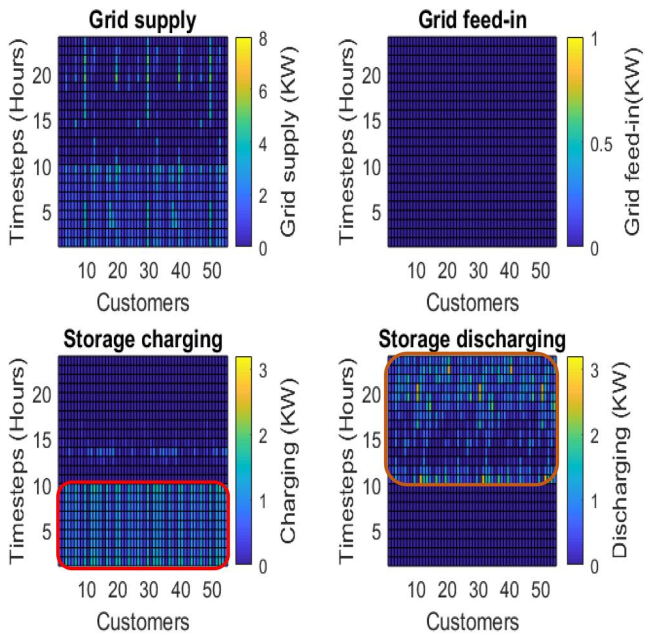

FIGURE 4 Grid interaction and storage operation for SO-PV + energy storage (ES) case in a winter month

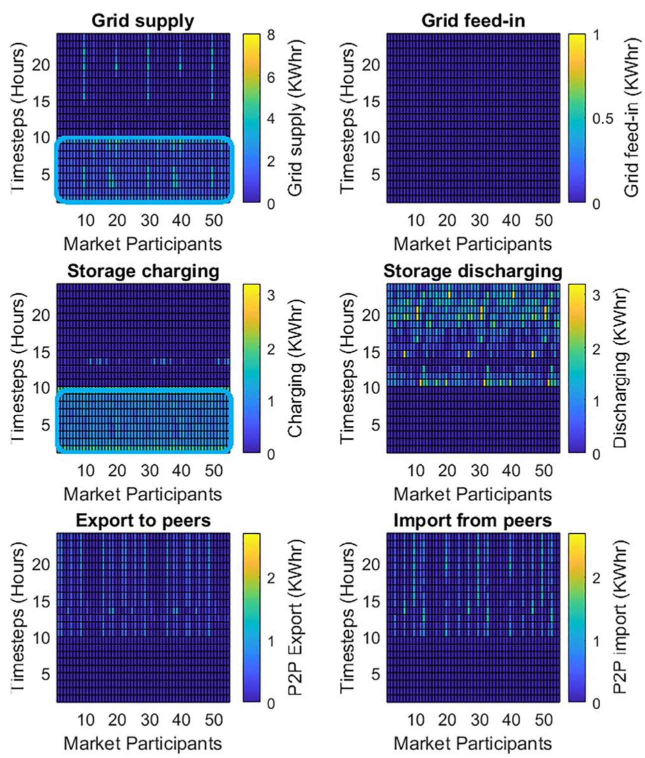

FIGURE 5 Grid interaction, storage operation and P2P transactions for LEM-PV + energy storage (ES) case in a winter month

trading of surplus electricity among peers who otherwise would sell the excess green electricity to the grid at a lower feed-in-tariff. Introducing ES in the summer month provided the LEM participants with the leverage to store surplus generation for later consumption. High self-sufficiency of the summer month due to high PV and low demand, keeps the need for energy arbitrage low. Therefore, P2P transaction in the LEM case for the summer month has a lower gap between the cases, LEM- PV and LEM-PV + ES, compared with the winter month. All of the cases have seen a reduction in the grid feed-in after the introduction of LEM referring to the maximisation of the utilisation of locally generated electricity.

For a detailed analysis of the market outcome, storage operation and the interaction of market participants with the grid and other peers for the two cases identified above, LEM-PV on summer month along with LEM-PV + ES on winter month, we have presented the results of 24 h of operation for each representative months. We opted for June 21 for the summer month, the day with a maximum-aggregated PV generation in June 2020 and January 16 for the winter month, the day with maximum aggregated demand for the community.

To begin with January 16, 2020, Figure 4 presents the SO-PV + ES case where customers primarily buy electricity from the grid up to 10:00 and charge their ES (marked in red square). This is because the lower retail price from midnight up to hours 10:00 motivates the customers to charge their ES in early hours to utilise stored electricity for the rest of the day (when the electricity price is high) to meet their demand. Therefore, storage discharging is taking place throughout the rest of the day after hours 10:00 (marked in the orange square).

Figure 5 illustrates the LEM-PV + ES case where the grid supply has reduced after-hours 10:00, although it has increased in an amount up to hours 10:00 (grid supply and ES charging is seeing more energy density, marked in light blue square, compared with the SO-PV + ES case in Figure 4) for some of the customers. The provision of P2P trading in the LEM case has encouraged some of the customers with the provision of storing excess energy, after meeting their own demand, to engage in energy arbitrage with other customers in need. Grid feed-in has not taken place in the case of LEM-PV + ES (Figure 5) whereas for SO-PV + ES (Figure 4) it is very low (only 41 kWh). This happens mainly as the generated PV has been mostly consumed on-site to meet the demand at peak hours and the self-sufficiency of the winter month is also very low. This proves that P2P trading is primarily driven by energy arbitrage rather than by the trading of surplus PV-generated electricity.

For the summer month, we begin with the LEM-PV case, which has the highest savings in terms of collective net energy cost. To better comprehend the LEM operation, at first the base-PV case on June 21, 2020, the day with maximum PV generation, has been presented. High grid feed-in has been observed as the

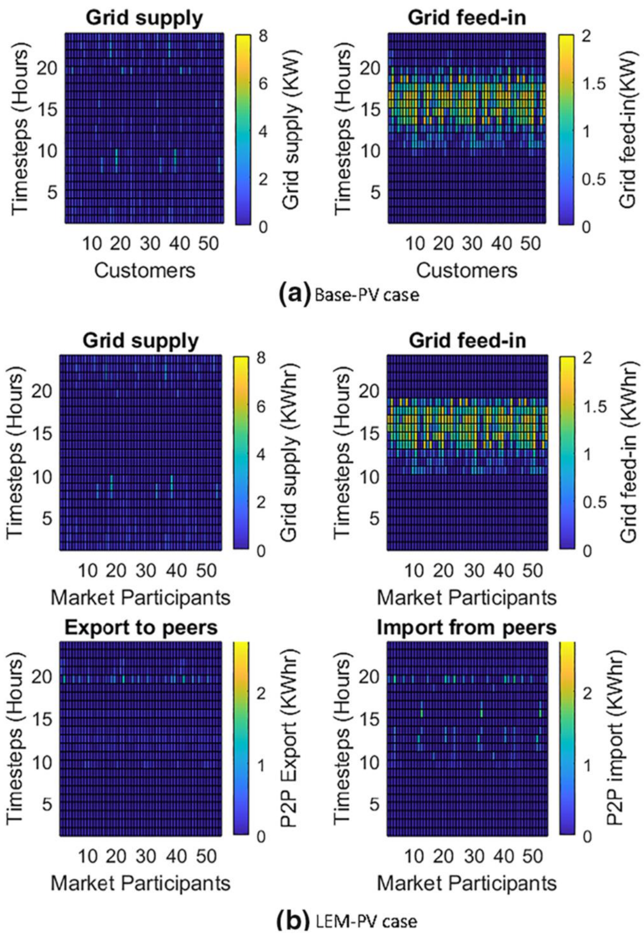

FIGURE 6 Grid interaction and P2P transactions for both base-PV and LEM-PV cases in the summer month

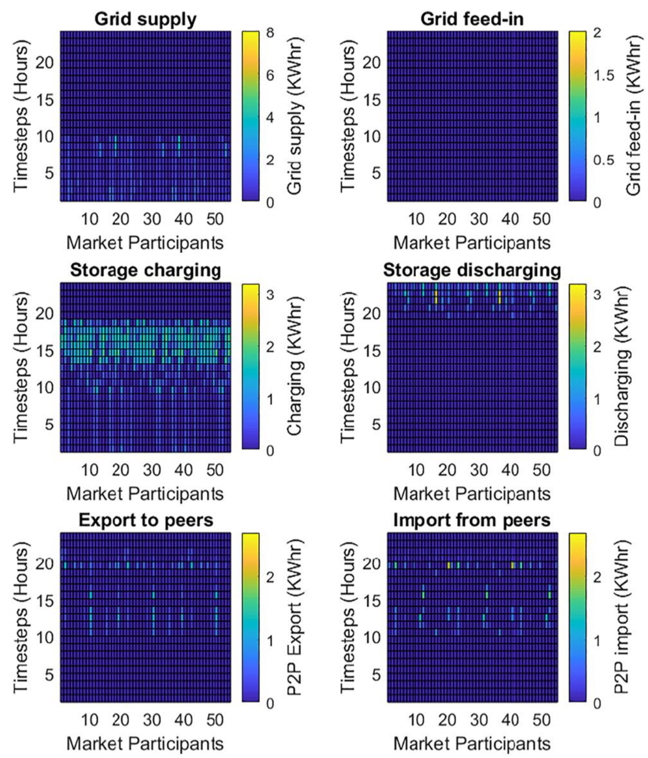

FIGURE 7 Grid interaction, storage operation and P2P transactions for the LEM- PV + energy storage (ES) case in a summer month

case does not have the provision of storing surplus electricity. With the introduction of LEM (LEM-PV case), the provision of trading surplus electricity has opened up and P2P trading is observed in Figure 6b. Nevertheless, the amount of P2P trading is not significant for the day as every customer is able to meet their demand from their own generated PV.

The absence of ES has eliminated the possibility of storing surplus electricity for later usage or for trading with peers at night. This has contributed to high grid feed-in in both cases as shown in Figure 6. With the integration of ES in the portfolio of customers, Figure 7 demonstrates the LEM-PV + ES case in the summer month, which shows that ES has opened up the possibility of storing surplus electricity reducing the grid feed-in to almost zero.

Moving on to the impact of the LEM operation on the network performance of LVDN hosting LEM, it can be seen from Table 3 that the winter month has seen under-voltage issues whereas the summer month has observed overvoltage problems. The allowable threshold for the under-voltage and over-voltage at customer connection points (customer nodes) have been considered to be 5% and 3%, respectively. The reason behind choosing a different threshold for overvoltage is that none of the customer nodes has encountered voltage over 5% for the studied cases. Therefore, a 3% over-voltage limit has been considered to understand the sensitivity of the situation as certain hours are experiencing voltage over that limit.

The inclusion of ES in customers' portfolios has deteriorated the voltage profile as the number of hours experiencing the under-voltage problem has surged. The worst situation happened in the LEM-PV + ES case in the winter month, which has seen under-voltage hours to be increased manifolds in Table 3. This is because of the high charging of ES taking place at low tariff hours. Both Figure 8a,b illustrate the voltage profiles of all the customers for consecutive 10 days in the middle of the winter month. It clearly indicates that the LEM has deteriorated the voltage profile due to the reason discussed before. It also depicts that the customers at the end of the network feeder (e.g. customers 35–37, 50, 52–53 and 55 in Figure 3) are generally severely affected. On the other hand, the summer month voltage profiles for the base-PV case (last 10 days), depicted in Figure 9a, are more subjected to the overvoltage problem due to the injection of surplus electricity into the grid from solar PV generation and LEM (LEM-PV case) does not improve the voltage profiles notably as shown in Figure 9b.

TABLE 3 Summary result of operating hours violating voltage thresholds

	Summer		Winter	
	Undervoltage hours in % ($V < 0.95$ p.u.)	**Overvoltage hours in % ($V > 1.03$ p.u.)**	**Undervoltage hours in % ($V < 0.95$ p.u.)**	**Overvoltage hours in % ($V > 1.03$ p.u.)**
Base-PV	0	0.33	0.63	0
SO-PV + ES	0	0	0.79	0
LEM-PV	0	0.33	0.63	0
LEM-PV + ES	0	0	3.4	0

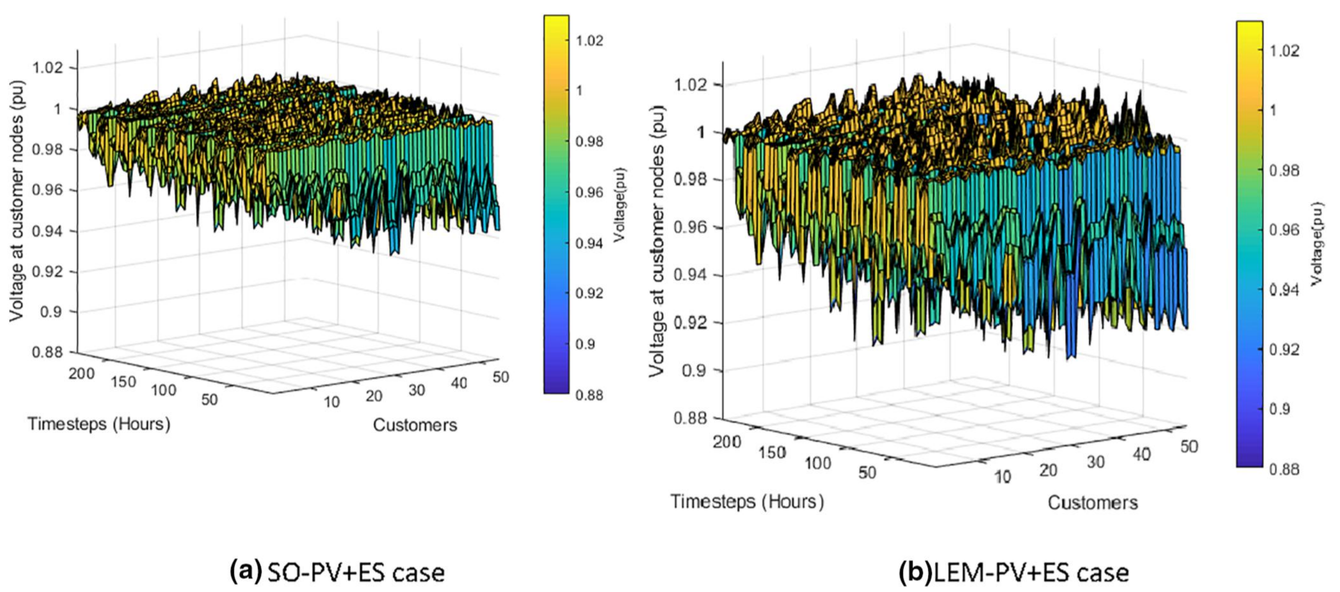

FIGURE 8 Voltage profiles of all customer nodes for both SO-PV + energy storage (ES) and LEM-PV + ES cases in a winter month

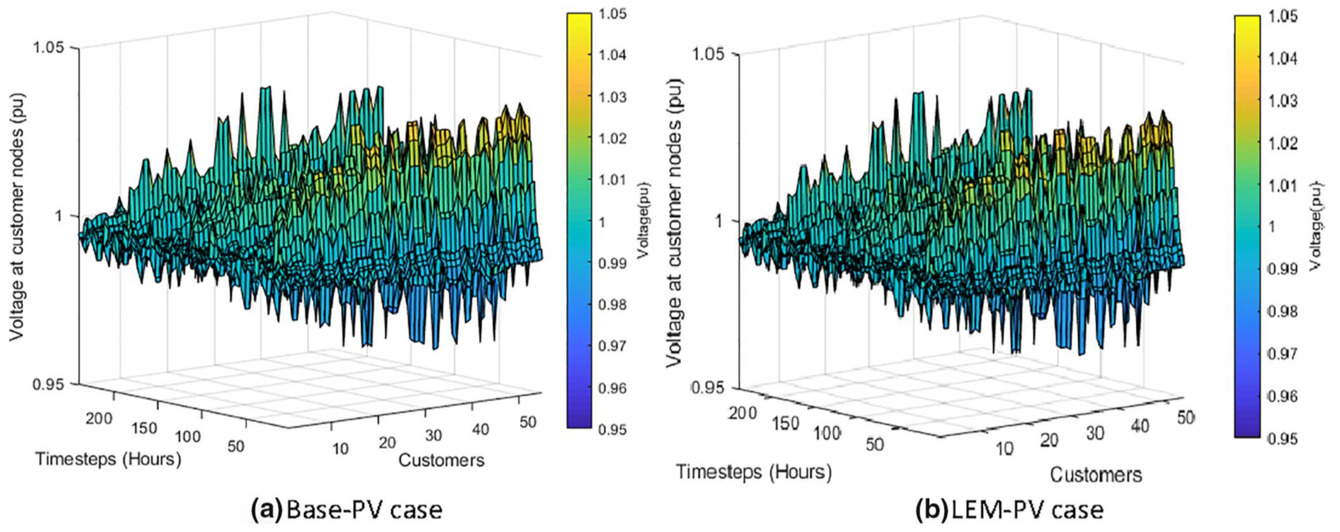

FIGURE 9 Voltage profiles of all customer nodes for both base-PV and LEM-PV cases in a summer month

TABLE 4 Power flow results for different cases

	Summer		**Winter**	
	Total active power exchanged (KWhr)	**Active power losses (in %)**	**Total active power exchanged (KWhr)**	**Active power losses (in %)**
Base-PV	6831	1.71	22,675	1.33
SO-PV + ES	7602	1.23	24,050	1.81
LEM-PV	6831	1.71	22,675	1.33
LEM-PV + ES	7462	0.99	24,623	2.65

Table 4 enumerates the energy flow through the LV feeder, downline from the MV/LV substation, hosting the LEM and active power losses for each of the cases. The LEM-PV + ES case in the winter month has seen the highest active power losses among the cases studied.

4 | CONCLUSIONS

The LEM proposed in the paper focussing on the local energy community with residential customers having different DER asset portfolios has succeeded in reducing the collective net energy cost, cost of energy exchange with the grid, of energy community through P2P transactions. The local electricity market boosts local consumption of locally generated, green electricity and is more impactful when the customers are having ES in their portfolio. The DER portfolio of roof-top PV and residential ES along with access to LEM has demonstrated better performance across the cases in terms of community benefit as flexibility of ES has been augmented by the flexibility of P2P trading in LEM. The key contributors to the benefits are collective self-consumption of local, green energy and energy arbitrage due to differential tariff schemes.

A key aspect of the paper is the impact assessment of LEM on the real-life, LV, radial distribution network hosting the market participants. The study has conducted the network power flow separately and subsequent to the market clearing. The most prospective case LEM-PV + ES in terms of community benefit has manifested poor network performance, for example, deteriorated voltage profiles at customer nodes and high active power loss. Extension of the properties of the proposed LEM structure to the flat and dynamic electricity pricing scheme and the inclusion of the ES degradation model are the authors' priorities for further research on the market model. Analysis on network performance will also be addressed in future research work where the substation congestion, and network unbalance study will be performed with the possibility of inclusion of network parameters in the market model to investigate the impact on the community benefit when the LEM model is subjected to certain network constraints. Future research will also explore the sequential rolling horizon method for clearing the market to take into account the uncertainty associated with generation and demand profiles.

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CONFLICT OF INTEREST

No.

DATA AVAILABILITY STATEMENT

Generation and consumption profiles of customers: Data available on request from the authors Network Data: Data openly available in a public repository that issues datasets with DOIs.

NOMENCLATURE

INDICES AND SETS

$p \epsilon P$	Market participants
$t \epsilon T$	Trading periods

PARAMETERS

λ_t^{Im}	Time-of -use tariff
λ_t^{Ex}	Feed-in-tariff
Δt	Duration of the trading period
$P_p^{\mathrm{ch,\ max}}$	Maximum charging power of energy storage
$P_p^{\mathrm{dis,max}}$	Maximum discharging power of energy storage
$\underline{E_p}$	Minimum capacity of energy storage
$\overline{E_p}$	Maximum capacity of energy storage
η_p^{ch}	Charging efficiency of energy storage
η_p^{dis}	Discharging efficiency of energy storage
$P_{p,t}^{\mathrm{dem}}$	Demand of market participant p at trading period t
$P_{p,t}^{\mathrm{gen}}$	Generated power from roof-top PV of market participant p at trading period t
$P_{p,t}^{\mathrm{inj}}$	Net injected power of market participant p to the grid at trading period t

VARIABLES

$P_{p,t}^{\mathrm{Im}}$	Active power imported by market participant p at trading period t from the retailer
$P_{p,t}^{\mathrm{Ex}}$	Active power exported by market participant p at trading period t from the grid
$P_{p,t}^{\mathrm{ch}}$	Charging power of energy storage
$P_{p,t}^{\mathrm{dis}}$	Discharging power of energy storage
$P_{q\rightarrow p,t}^{\mathrm{P2P\ buy}}$	Active power purchased by market participant p from peer q in trading period t in the LEM
$P_{p\rightarrow q,t}^{\mathrm{P2P\ sell}}$	Active power sold by house p from peer q in trading period t in the LEM
$E_{p,t}$	State-of-charge of battery energy storage

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