Local Electricity Market Operation in Presence of Residential Energy Storage in Low Voltage Distribution Network: Role of Retail Market Pricing

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Funder: This work is partly supported by the BEYOND project, funded by the joint programming initiative ERA-Net Smart Energy Systems, co-funded by the European Union's Horizon 2020 research and innovation programme under grant agreement no 775970, Sustainable Energy Authority of Ireland - Grant Agreement 19/RDD/578 and IEA USER TCP task GO-P2P in IERC . The authors in IERC thankfully acknowledge the support from the Department of the Environment, Climate and Communications and the Sustainable Energy Authority of Ireland.

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Energy Reports 9 (2023) 5799–5811

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

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ARTICLE INFO

Article history:
Received 5 January 2023
Received in revised form 8 April 2023
Accepted 4 May 2023
Available online 19 May 2023

Keywords:
Energy storage
Local Electricity Market
Low voltage distribution network
Peer-to-peer transactions
Retail electricity pricing

ABSTRACT

Local Electricity Market (LEM) appears as a promising consumer-centric market-based approach that extends the self-consumption method, widely implemented in residential households, to collective self-consumption in the local energy communities, enabled through peer-to-peer (P2P) transactions. To facilitate the integration of LEM in the wholesale electricity market (WEM), it is paramount to comprehend the synergy of retail electricity pricing on the LEM operation hosted in the low-voltage distribution network (LVDN). The paper presents a co-simulation framework consisting of a local electricity market model coupled with a three-phase distribution network simulator to perform a holistic case study for a smart energy community in Ireland. The novel contribution of the work is to explore the potential of local electricity trading in the presence of residential energy storage (ES), under different retail pricing schemes existent in Ireland, by evaluating economic benefits to the energy community and network performance of three-phase LVDN. Extensive simulation studies indicate that the presence of residential ES significantly boosts P2P transactions under static time-of-use (SToU) pricing. These P2P transactions are primarily contributed by energy arbitrage (among customers in LEM) in the winter and surplus PV-generated electricity in the summer. On the other hand, the scheduling of ES under SToU pricing deteriorates the network performance of LVDN in winter, showing the highest active power loss and under-voltage scenario among all the cases. Another unique aspect of LVDN is the voltage unbalance studied and found to be highly correlated with ES operation under SToU pricing. Recommendations have been made to the relevant stakeholders and market actors, identifying key aspects necessary to roll out the LEM under retail electricity pricing schemes.

1. Introduction

1.1. Background and motivations

The European strategic energy technology (SET) plan presents the energy strategy at the European level to achieve a climate-neutral energy system in Europe by 2050 (European Commission, 2022). This strategic plan envisages a consumer-centric energy system which places energy end-users at the core of the upcoming energy system (European Commission, 2019). Actual deployment of distributed energy resources (DERs) in the residential premises, e.g. rooftop Photovoltaics (PVs), energy storage (ES), electric vehicles etc., along with wide-scale integration of smart meters and energy management systems, are expediting the transformation of passive consumers to prosumers/active consumers. Energy communities can contribute enormously to paving the way to deal with financial and organisational challenges associated with the such transformation of the consumers (Chicco et al., 2021). A range of services and activities fit the energy community concept, though all of them are not defined in the European Union framework. The local electricity market (LEM) is one such 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 (Mengelkamp et al., 2018; ENTSOE and Local Energy Trading, 2022). However, it is unlikely that the community will have self-sufficiency across the operational time horizon. Therefore, it requires to depend on the central wholesale electricity market (WEM) to maintain the security of supply. Currently, residential customers only engage in the retail electricity market (REM), where consumers have long-term contracts with electricity retailers (Wilson, 2002).

Retail electricity pricing usually constitutes energy price and network tariffs, taxes, levies, and suppliers' operating costs. The

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https://doi.org/10.1016/j.egyr.2023.05.005

two main components of retail electricity pricing, which can vary dynamically across time, are energy price and network tariff. The former reflects variation in the WEM price, and the latter relates to energy delivery cost through distribution and transmission networks. The national energy regulatory body determines the network tariff for residential households to recover the cost of energy delivery by the network operators. This tariff also comprises three components: energy (per kWhr), power (per kW) and fixed time (per year). Historically, retail electricity pricing schemes include fixed-price, static time-of-use (ToU) price, dynamic time-of-use prices, etc. (Defeuilley, 2009), and have their variation originating from the distribution network (DN) tariff component. Some of the EU countries have recently placed dynamic retail electricity pricing with variation driven by spot market price, e.g. real-time pricing, at the household level (IRENA, 2019; EURELECTRIC, 2017), and some others are in the process of introducing it (Commission Staff Working Document, 2019). However, spot market price-driven dynamic pricing has yet to be widely implemented for various barriers (Matisoff et al., 2020; Bhagwat and Hadush, 2020). As a result, most of the existing variation in retail electricity pricing is principally driven by the network tariff component.

The design of electricity pricing for residential customers in REM is primarily motivated by the system-level factors, e.g. generation portfolio, electricity demand variation, policy on integrating non-dispatchable DERs and transmission-/distribution-level network (TN/DN) constraints etc. Conversely, it must be made aware of the specific aspects of the low-voltage distribution network (LVDN), residential customers, and the types of DER assets hosted on such networks. However, the REM pricing scheme is the market interface between the residential customers and the central WEM and carries significance in transforming residential customers towards activism. Therefore, deploying any consumer-centric market approach, such as the LEM, requires a comprehensive study analysing the critical aspects of LEM operation hosted in LVDN under the existing REM pricing schemes.

1.2. Literature review

Price responsiveness for different types of controllable DERs, such as electric vehicles (EV), energy storage (ES), heating systems etc., has been studied extensively in the literature. The most popular and granular demand response (DR) approaches are the self-optimisation (SO) method, maximisation of self-consumption and bill minimisation using a home energy management system (HEMS). It schedules dispatchable DERs based on retail pricing schemes (Haque and Wolfs, 2016). Retail price invokes implicit DR on a residential level, with customers shifting/keeping their demand away from times of high prices. The impact of exogenous retail pricing on residential DR has been studied in Wang et al. (2015), Zugno et al. (2013), Yazdani-Damavandi et al. (2018), Li et al. (2022), Contreras-Ocaña et al. (2019) and Bruninx et al. (2019), where the relationship model between the retailer/aggregator and the customer has been discussed. Authors in Wang et al. (2015) and Zugno et al. (2013) have modelled the relationship as mixed-integer linear programming (MILP) and the Stackelberg game, respectively. Authors in Yazdani-Damavandi et al. (2018) have shown the results for DERs with multi-energy vector features. Authors in Li et al. (2022) have proposed deploying a dynamic reinforcement-based learning framework in the real-time scheduling of residential appliances. Nash equilibrium game theory has been used in both Contreras-Ocaña et al. (2019) and Bruninx et al. (2019), for the energy storage (ES) system and thermostatically controlled loads, respectively.

Another direction of this study focuses on retail pricing, specifically on the distribution network (DN) tariff component. As previously mentioned, the DN tariff is paramount for retail pricing as the variation in widely-implemented retail pricing emanates from different tariff structures. There are two primary directions of research related to this DN tariff. Firstly, many researchers have studied the impact of DER assets and residential customer types on the design attributes, e.g. cost-reflectivity, cost recovery, fairness etc., of DN tariffs (Askel et al., 2020; Hoarau et al., 2019; Schittekatte, 2020). Authors in Askel et al. (2020) have presented an optimal grid tariff design acting as a price signal to reduce network peak. Authors in Hoarau et al. (2019) have examined the distinct impact of DERs and mainly EVs on network cost recovery. Authors in Schittekatte (2020) have quantified the economic impact of residential PV and ES under different tariff structures on the network investment cost and network revenue and conclude that the investment cost reduction can offset the network revenue reduction. Similarly, cost-reflectiveness and fairness attributes of the network tariff design have been investigated in Schittekatte (2020) and have presented the relationship between active and passive consumers with the facts. Authors in N et al. (2022) have evaluated the performance of six different network cost allocation methods in pay-as-bid P2P energy trading and present a comparative analysis to determine market efficiency. The second trend of research focuses on the impact assessment of DN tariff structures on the techno-economic feasibility of residential DER assets, benefits on customer types etc., in an inverse way of the first one. PV and ES combination investment planning has been studied for flat, dynamic, and ToU tariffs in Parra and Patel (2016). The uptake of EV transition under different tariff schemes has been scanned in McKinney et al. (2023) with a focus on EV charging in rural areas. Authors in Avau et al. (2021) have studied the impact on customers' self-consumption for five different distribution tariff structures and four DER asset combinations. It shows that dynamic distribution tariff structures stimulate self-consumption by increasing energy supply costs. Authors in Schittekatte et al. (2018) have shown that improper network tariff design results in a lack of efficiency and equity for DER assets. The regulatory aspect of local energy communities and associated grid tariffs has been presented in Maldet et al. (2022) for Europe, with an analysis focusing on LEM in Austria, Ireland, and Norway.

The study conducted in this paper differs from the research mentioned above trends, shifting the focus on the interaction between LEM operation and REM pricing, which has yet to receive very little attention. The LEM extends the self-consumption approach (typical operating principle of a home energy management system) towards collective self-consumption and usually utilises the retail pricing as a unidirectional, downstream price signal influencing the LEM operation (Capper et al., 2022). LEM operation possesses two-dimensional flexibility: implicit demand response from flexible DERs and flexibility originating from peer-to-peer (P2P) energy transactions among customers in the energy community. Hence, any adjustment in one dimension has consequences on the other dimension. Therefore, it suggests that the interaction of retail pricing on LEM operation significantly differs from the self-consumption approach. Authors in Askel et al. (2021) have presented the results on the cost recovery of the DN due to the establishment of LEM and have found that it reduces the need for grid capacity improvement. However, the work has not quantified LEM's customer/community benefits compared to other uncoordinated schemes. Authors in Neves et al. (2020) have worked on that gap and analysed the economic benefits of residential customers brought by the P2P local market for different penetration of solar PV and load flexibility under various retail pricing schemes. This work is oblivious to the low-voltage distribution network (LVDN) hosting the LEM, which is crucial for the real-life roll-up of the LEM framework. Another investigation aspect requiring specific attention is that the residential ES appears as a pivotal technology and is distinct from other flexible DERs, with its temporal flexibility attribute. This flexibility enables ES to determine when it can become an energy/power source or sink, empowering customers to maximise self-consumption and energy arbitrage. Under the LEM framework, the flexibility of P2P transactions notably influences ES scheduling consequences on LEM outcome and LVDN performance, as shown by the authors in their previous work (Saif et al., 2022). It is because the provision of P2P transactions extends the periphery of self-consumption and energy arbitrage from a single household to the community. From the detailed literature review given above, the authors of this paper have not found any work addressing the synergy of retail pricing with LEM operation and LVDN performance in the presence of residential and distributed ES.

1.3. Contributions

This paper presents a comprehensive study using a co-simulation modelling approach to minimise this gap. Furthermore, this study has been conducted for a real-life local energy community in Ireland. The study implements Ireland's retail pricing schemes: flat and static time-of-use pricing. The novelty of the paper is to minimise the research gaps in the literature with the following key contributions:

- The paper critically assesses the synergy among exogenous REM pricing, LEM operation, ES scheduling and LVDN performance.
- The impact of ES in the LEM framework on LVDN under existent REM pricing schemes through the developed simple modelling approach.
- Three-phase power flow analysis on a real-life European LVDN hosting LEM. The co-simulation modelling approach adhered to LEM outcome in an unrestrained network way and simultaneously conducted a three-phase, unbalanced power-flow-based quantitative assessment of LVDN.
- Analyse the extreme case scenarios during summer and winter to understand the seasonal impacts on the LEM operation and network.
- All the above aspects of the study have been conducted under two REM pricing schemes — the existent flat and static ToU pricing in Ireland, which is the novel contribution of the paper.

This study demonstrates a better understanding of the consumers' active participation in the energy transition – which is better – self-consumption/optimisation or collective self-consumption with P2P energy transaction provision and their impact on the network performance. Furthermore, it investigates key network performance metrics, e.g. line loss, over-voltage/under-voltage condition at customer nodes, and voltage unbalance, a network performance indicator unique to LVDN. Finally, recommendations have been made from the comprehensive assessment of the stakeholders and market actors for the real-life roll-out of LEM. The rest of the paper is organised as follows: market architecture and modelling approaches have been presented in Section 2. Section 3 has described test case scenarios followed by the simulation results and analysis. Finally, conclusions have been made in Section 4.

2. Methodology

2.1. Market architecture

The LEM envisioned in the paper is focused on 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 residential battery ES stimulates the local trading of electricity and impacts the distribution network.

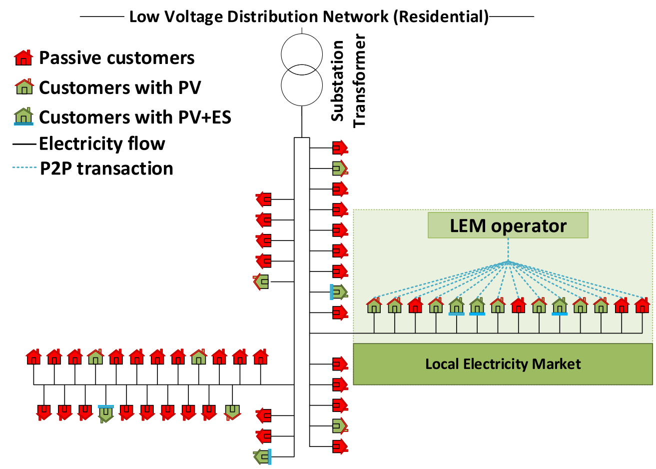


Fig. 1. Local electricity market architecture.

It is logical that LEM participants collectively will not have self-sufficiency/well-balanced energy across all market periods in the operational time horizon. Hence, an energy exchange mechanism is required between the LEM and the central WEM to maintain the security of supply. This work considers that the electricity retailer/utility supplier is responsible for meeting the surplus/deficit energy of market participants (after the settlement of P2P transactions) in a business-as-usual way. The other vital actors in this market mechanism are the local electricity market operator (LEMO), distribution system operator (DSO) and market participants (electricity customers: producers, prosumers and consumers). The role of the LEMO involves managing the P2P transactions among the market participants to reach the goal of the LEM. DSO ensures the P2P transactions in the LEM operation adhere to the network's technical constraints. Fig. 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 the status and characteristics of DER assets, e.g. state-of-charge of batteries, maximum charging/discharging limits etc. Therefore, LEM is considered to interact with REM only and has no direct involvement with the WEM.

2.2. Modelling approach

A two-stage co-simulation and cascaded modelling approach have been implemented for this study. Such a modelling approach aims to provide distribution system operators with the capability to model the impact of LEM on the LVDN, a crucial stage for the wide-scale roll-out of LEM hosted in the LVDN. The two stages comprise (i) the individual self-optimisation (SO) model or collectively optimised LEM model and (ii) the LVDN power flow model. The former stage is an energy management/market model that schedules the DER assets at the customers' premises to meet the objectives defined in the test scenarios elaborated in Section 3.2. The latter stage is the power flow model incorporating network topology and network assets' characteristics of the LVDN. SO conducts DER assets' scheduling of individual customers separately, aiming only for the customer's benefit. In contrast, the LEM functionality provides P2P transactions among customers and the capability of scheduling DER assets. The SO/LEM stage modelling is developed in MATLAB using the open-source optimisation modelling language, YALMIP (Lofberg, 2004) and MOSEK (MOSEK, 2022) as an optimisation solver. Upon completion of the first stage, dispatches of the DER assets are utilised in the second, subsequent LVDN power flow stage to conduct network performance due to the operation of SO/LEM under different REM pricing schemes. An open-source grid simulator, OpenDSS (Dugan and McDermott, 2011) is used to perform the time-series simulation of the complex, unbalanced, 3-phase distribution network.

2.2.1. SO/LEM stage

For the SO/LEM stage, a linear multi-period optimisation model is formulated for a set of customers, $P = \{1, 2, \ldots, N_p\}$ across a market horizon, T with trading period denoted by t having market time duration ΔT to describe the LEM framework. Both functionalities under the SO/LEM stage are aimed at minimising electricity procurement and maximising the revenue from exporting electricity to REM. As the objectives are similar for SO and LEM, the objective function for this novel modelling approach is expressed by a simple and ordinary Eq. (1) (Ibn Saif et al., 2021; Saif et al., 2023),

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

where, λ_t^{Im} is the time-of-use retail electricity price, λ_t^{Ex} is the grid feed-in tariff, $P_{p,t}^{Im}$ represents the amount of electricity procured from the grid and $P_{p,t}^{Ex}$ represents the amount of electricity sold to the grid. The first term of the objective function describes the cost function related to buying electricity from REM under different pricing schemes. The second term refers to the revenue function denoting electricity exported to the grid at a feed-in-tariff rate.

The optimisation problem under the SO/LEM stage for both functionalities is subjected to a set of constraints and broadly categorised as DER operational constraints, energy balance constraints and P2P transaction constraints. As energy storage (ES) is one of such critical DER assets and getting more importance in residential premises, this study gives significant weight to understanding their impacts on the market outcome and network performance. The charging power $P_{p,t}^{ch}$ and the discharging power $P_{p,t}^{dis}$ of the ES is limited by the inverter size. The upper and lower limit of state-of-energy $E_{p,t}$ is bounded by the ES capacity. A binary variable $u_{p,t}$ signifying the operating mode of the ES is also incorporated. If ES is charging for customer p at trading period t, then $u_{p,t} = 1$, ; otherwise, while discharging, it takes $u_{p,t} = 0$ and it can hold any binary value while in idle mode. A constraint has also been enforced, setting the initial and final energy level of ES to be minimum for continuity. The above-mentioned ES constraints are expressed as follows,

$$P_{p,t}^{ch} \leq P_p^{ch,max} u_{p,t} \tag{2}$$

$$P_{p,t}^{dis} \leq P_p^{dis,max} \left(1 - u_{p,t}\right) \tag{3}$$

$$\underline{E_p} \leq E_{p,t} \leq \overline{E_p} \tag{4}$$

$$E_{p,1} = \underline{E_p} \; \& \; E_{p,T} = \underline{E_p} \tag{5}$$

A simplified linear formulation is used to model energy storage (ES). It is assumed that the charging/discharging power is constant during the trading period and the state of energy of the ES ($E_{p,t}$) is governed by,

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

where, η_p^{ch} and η_p^{dis} are the ES charging and discharging efficiency.

Energy balance constraints for each market participant need to be respected for each trading period, t. This constraint ensures that the summation of injected power in terms of grid import $P_{p,t}^{Im}$, purchased electricity through P2P transactions from other market participants $\sum_{q \neq p} P_{q \to p,t}^{P2P\,buy}$ (implemented under LEM functionality only), ES discharge $P_{p,t}^{dis}$ and self-generated power $P_{p,t}^{gen}$ must satisfy the load $P_{p,t}^{dem}$, ES charging $P_{p,t}^{ch}$, sold electricity in P2P transactions to others $\sum_{q \neq p} P_{p \to q,t}^{P2P\,sell}$ (implemented under LEM functionality only) and grid export $P_{p,t}^{Ex}$. μ^{loss} is a co-efficient denoting network loss factor affiliated with P2P transactions (Ibn Saif et al., 2021; Saif et al., 2023).

For SO,

$$P_{p,t}^{Im} + P_{p,t}^{dis} + P_{p,t}^{gen} = P_{p,t}^{Ex} + P_{p,t}^{ch} + P_{p,t}^{dem} \tag{7}$$

For LEM,

$$P_{p,t}^{Im} + \sum_{q \neq p} P_{q \to p,t}^{P2P\,buy} + P_{p,t}^{dis} + P_{p,t}^{gen} = P_{p,t}^{Ex} + \mu^{loss} \sum_{q \neq p} P_{p \to q,t}^{P2P\,sell} + P_{p,t}^{ch} + P_{p,t}^{dem} \tag{8}$$

The final constraint only applies to the LEM and focuses 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 t.

$$\sum_{p} \sum_{q \neq p} P_{q \to p,t}^{P2P\,buy} = \mu^{loss} \sum_{p} \sum_{q \neq p} P_{p \to q,t}^{P2P\,sell} \tag{9}$$

where, $P_{q \to p,t}^{P2P\,buy}$ corresponds to the electricity purchased by house p from peer q in the LEM and $P_{p \to q,t}^{P2P\,sell}$ corresponds vice-versa.

2.2.2. LVDN power flow stage

From the network operational perspective, the power flow simulation examines the impact of DER dispatches resulting from the operation of SO/LEM. Therefore, it requires the LVDN model, which describes the network topology and characteristics of the network assets and conducts power flow simulation on each market outcome horizon trading period. The outcome of the previous SO/LEM stage is used to create net injection profiles of each customer at connection points to the LVDN. Net injection profiles, $P_{p,t}^{inj}$ of each customer p at each trading period, t is calculated by,

For SO,

$$P_{p,t}^{inj} = P_{p,t}^{Im} - P_{p,t}^{Ex} \tag{10}$$

For LEM,

$$P_{p,t}^{inj} = P_{p,t}^{Im} + \sum_{q \neq p} P_{q \to p,t}^{P2P\,buy} - P_{p,t}^{Ex} - \sum_{q \neq p} P_{p \to q,t}^{P2P\,sell} \tag{11}$$

Hence, the net profile is calculated from the sum of the active power imported to the connection point minus the sum exported from the connection point. The operation of the ES is taking place behind the meter and is therefore not included in Eqs. (10) and (11). Eq. (11) accounts for the export and import power resulting from the P2P transactions inside LEM and the export and import power resulting from energy exchange with REM, as described in Eq. (10). Even though the SO/LEM stage is based on dynamic power flow, the power flow model requires active and reactive power profiles. This LVDN power flow stage considers a constant power factor. Thus the reactive power is calculated from the dynamic power profile with a constant power factor.

3. Case study

3.1. Data

The study is conducted on 55 residential households considering each house has a rooftop PV system (ranging from 2–2.2 KWp)

Table 1
Descriptions of the test cases based on retail pricing schemes.

Descriptions of scenarios
Flat pricing This case has been presented as a base case for the study. Under this pricing scheme, the pricing signal is time-invariant, being the same all around the day across the year. Therefore, this pricing scheme does not incentivise the customers to demand response.
Static ToU (SToU) pricing This case segregates the hours in the day into a specific number of time blocks, each having several hours. The price of electricity for each time block is announced beforehand and remains constant. For this study, the day–night pricing scheme in Ireland in 2020 has been used. It has two-time blocks: low pricing hours, starting from midnight till 8 a.m., with prices almost half the price of high pricing hours spanning the rest of the day.

and ES (10 kWh/3.3 kW peak lithium-ion battery-based energy system). The PV production and consumption profiles used in the paper are real-life measurements from the smart meters installed on residential homes in a neighbourhood in the Dingle peninsula in Ireland (ESB Networks, 2022). The consumption profiles are considered inflexible, and residential ES is the only DER asset managed by the SO/LEM, providing flexibility from the customers' side. Ireland's existing REM pricing scheme is the retail tariff pricing used as input to the model. The retail pricing comprises wholesale energy cost, supplier's cost, grid tariff and government taxes, and levies (CRU, 2022). In 2020, domestic consumers in Ireland with static ToU pricing were charged 20.07 c€/kWh and 9.91 c€/kWh, respectively, in day and night time zones. The electricity export to the retailer is assumed on the fixed tariff of 9.0 c€/kWh. For the flat pricing case, the electricity price is constant at 20.07 c€/kWh throughout the day, with the feed-in tariff the same as the former.

The energy storage system is constrained, with the minimum and maximum energy limits being 20% and 100%, respectively. The efficiency of the ES is assumed to be independent of the state-of-charge level and constant (95%) throughout the charging and discharging cycle. The study has considered two separate months to understand the impact of seasonal variation: January (winter) and June (summer) of 2020. Two extreme cases (load consumption and PV generation are at their maximum level) are also considered.

The IEEE European, low voltage test feeder, is taken as a test network, a radial, 3-phase distribution feeder (IEEE PES AMPS DSAS Test Feeder Working Group, 2022), and is supplied by an 11 kV/0.416 kV substation with a capacity of 350 kVA and delta/grounded-wye connection. The test feeder comprises 906 buses and 55 connection points (load nodes) for single-phase residential customers. All the customers are connected in different phases at different connection points across the test network, as shown in Fig. 2. Both market and power flow models are considered to operate on hourly resolution.

3.2. Test cases

This paper considers two test cases based on the retail tariff schemes in the year 2020. The results in the following section have been presented for both SO and LEM (as described in Section 2.2), which are studied under each case, elaborated in Table 1.

3.3. Simulation results

3.3.1. Impact of REM pricing scheme and ES operation on LEM

Fig. 3 shows the **monthly aggregated** simulation results for the entire month for the scenarios elaborated in Section 3.2. The percentage calculations in Fig. 3(a) and (b) are relative to the energy community's total demand for the entire simulation month. For all scenarios, the retail pricing (flat and SToU) impacts the DER scheduling and energy exchange with REM, thus with the SO and LEM approaches. For winter (Fig. 3(a)) and summer (Fig. 3(b)), compared to flat pricing, SToU pricing clearly shows more "REM supply". This happens due to the presence of ES and its energy arbitrage attributes (ES imports energy at low price hours, stores it, and meets the self-demand or sells it to other customers at high price hours through P2P transactions). For winter month, the "REM supply" increases between LEM cases (LEM-Flat: 87.52% and LEM-SToU: 92.83%), appearing at 5.31% (92.83–87.52). Summer month follows the same attributes, and REM supply increases by 2.59%. Similar trends are observed for the SO cases, where the increases are around 3.96% and 5.58%, respectively. It is also observed that, in the winter month, the "Flat" tariff scheme has less impact on the SO and LEM operation modes. Compared to LEM-Flat, REM supply rises very little, only 0.32%, in the case of SO-Flat. On the other hand, the "sToU" tariff scheme impacts the LEM operation and REM supply more. Compared to SO-sToU, REM supply increased by 1.03% for the LEM-sToU case. This happens due to the pricing differences under the sToU scheme, which increases energy arbitrage provision through P2P transactions, and the low generation-to-demand ratio pushes the ES operation heavily. The observation is the opposite in the summer month. In both tariff schemes (Flat and SToU), compared to the SO case, LEM reduces the REM supply significantly. In the Flat tariff scheme, it is 4.85% (44.57–39.72) and for the sToU case, it is 7.84%.

The percentage of ES charging function for both SO and LEM cases in winter months under both retail pricing schemes also indicates a similar phenomenon. Conversely, the summer month possesses a higher generation-to-demand ratio, and therefore, ES operation is driven by primarily storing surplus generation for later usage rather than energy arbitrage. The P2P transaction provision in LEM has caused the sharing of excess energy, reducing both REM supply and REM feed-in compared to SO cases. Under SToU pricing, the REM feed-in goes down by 7.36% for the LEM case compared to the SO case implying the localised consumption of surplus generation among peers. Throughout all scenarios, compared to SO, the introduction of LEM has maximised the local consumption of locally generated electricity which is indicated by the reduction of "REM feed-in". It is also interesting to note that the "REM feed-in" is higher for SToU pricing than the same scenario under flat pricing. This is because of the DER scheduling, designed to be operated (under both SO and LEM scenarios) to minimise the net supply cost. This is evaluated from Eq. (1) and is defined as the net cost of energy exchange of the energy community with the REM. The differential pricing under the SToU case and the feed-in tariff scheme has resulted in ES being utilised primarily for energy arbitrage, causing higher energy export to earn revenue through the feed-in tariff. This also increases the P2P transactions under LEM. In winter month, compared to Flat pricing, P2P transactions significantly increased by 11.42% for the SToU-LEM case. In this case, even though the PV generation is low but the load demand is high, customers engage in energy arbitrage with their peers. In contrast, the amount of P2P transactions is much closer for both scenarios under LEM in summer, with a difference of rise for the SToU-LEM case is around 1.46% . It is because the summer month has low energy arbitrage among peers due to high PV generation and low demand. The P2P transaction for the Flat-LEM scenario is higher by 6.9% for the summer month compared to the winter month, and it means that the P2P transaction in the summer month is driven by sharing surplus energy among peers. It can be seen from Fig. 3(c) and (d) that the introduction of LEM has reduced the net supply cost for all the scenarios. This indicates the economic benefits brought by

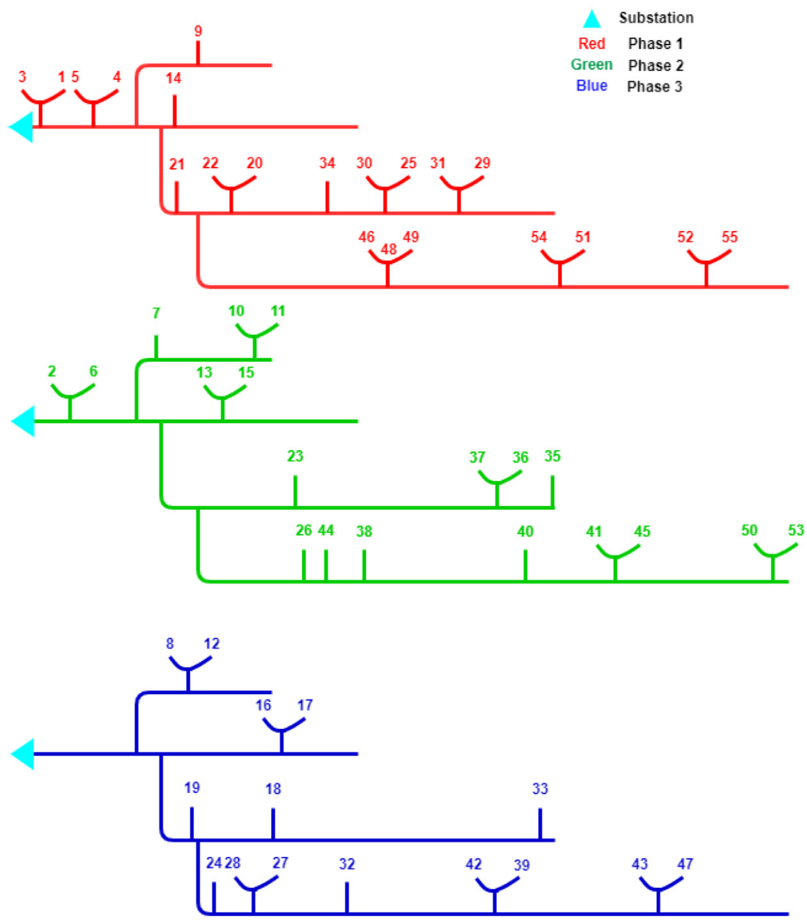


Fig. 2. Schematic diagram of IEEE LVDN test system identifying customer connection points.

LEM to the energy community compared to the SO scenarios. It can be observed that the economic benefit of LEM is higher under SToU pricing compared to flat pricing.

The key statistical excerpt from Fig. 3 has been enumerated in Table 2,

Table 2
Key statistical excerpt from Fig. 3.

	Winter	Summer
Increase of REM supply between SToU-LEM and Flat-LEM	5.31%	2.59%
Increase of REM supply between SToU-SO and Flat-SO	3.96%	5.58%
Increase of REM feed-in between LEM-SToU and LEM-Flat	0	1.01%
Increase of REM feed-in between SToU-SO and Flat-SO	0.1%	3.94%
Difference between P2P transactions in SToU-LEM and Flat-LEM, respectively	11.42%	1.46%

For an in-depth analysis of market outcome, ES operation, and market participants' interaction with REM and other peers for the cases identified above, a **day (24 h)** performance for each representative month is performed. We opted for 21st June for the summer month, the day with a maximum aggregated PV generation in June 2020, and 16th January for the winter month, the day with a maximum aggregated demand for the community.

First, the analysis begins with cases demonstrating the maximum reduction of imported energy from REM for each season. It is seen that imported energy is reduced most for flat pricing cases in the winter and summer months. Both SO and LEM cases under the winter day in Fig. 4 illustrate that the energy community's demand is met by REM supply, and PV generation is mainly consumed at the premises. However, there are a few hours, hours 13–14 (marked as the green and yellow boxes in Fig. 4(a) and (b) respectively), where the community has excess PV generation than demand. Therefore, it utilises flexibility in terms of ES (for SO case, marked in a green box in Fig. 4(a)) and P2P transaction (for LEM case, marked in a yellow box in Fig. 4(b)) to reduce REM dependency by utilising locally generated PV electricity. This trend of operation occurs throughout the winter month for flat pricing cases. As PV generation is low compared to the demand in the winter month, the introduction of LEM has an insignificant impact on the flat pricing scheme. However, the ES operation is augmented as the pricing scheme moves to SToU pricing. As a result, REM interaction is significantly changed, as shown in Fig. 5, compared to the cases illustrated in Fig. 4. This is primarily driven by the energy arbitrage opportunity brought by the SToU pricing scheme. Therefore, P2P exchange is more prevalent in the SToU case.

In the summer month, the SToU pricing case presents the highest reduction in REM dependency. Fig. 6 illustrates the representative summer day with maximum aggregated PV generation. REM supply has significantly been reduced and mainly occurs in low-price hours. ES charging takes place at hours when excess PV generation is available. Provision of P2P transaction clearly reduces the REM feed-in significantly, as depicted in LEM-SToU Fig. 6(b) (LEM-SToU case) in contrast with SO-SToU case (Fig. 6(a)). It demonstrates the utilisation of PV generation within the community, reducing reliance on REM-supplied energy. Fig. 6 also indicates ES charging has decreased significantly at low pricing hours. This suggests that the energy arbitrage has become less

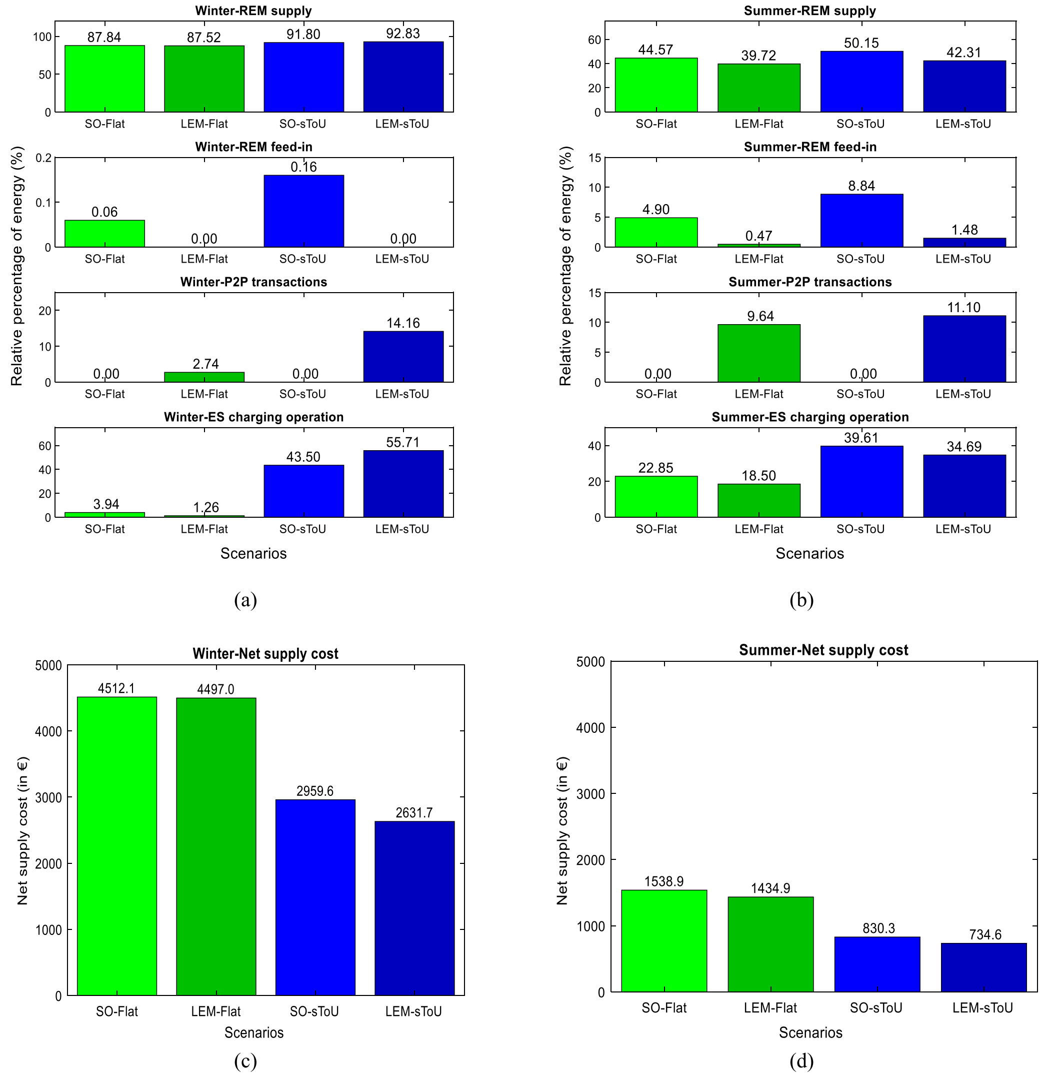


Fig. 3. Comparative analysis among different scenarios — (a,c) winter month and (b,d) summer month.

critical on summer days (and respectively in summer months, as shown in Fig. 3) and is even insignificant with the introduction of LEM due to the flexibility offered by P2P transactions. To understand the critical impacts of ES on the LEM and LVDN, the case studies in this paper have considered that all of the customers have ES facilities and thus enjoy the DER flexibility. The studies also have not delved into the impact of the REM pricing mechanism on the community under different penetration of DER flexibility. However, this assumption of DER flexibility having 100% penetration allows the study to identify the impact of P2P flexibility on the energy community under different REM pricing schemes.

3.3.2. Impact on the network

Network loss:

Fig. 7 shows network loss across different scenarios (the percentage of total energy exchanged across the feeder). Winter month appears as the critical season as the network losses are more likely, and this demands that network reinforcement planning is determined by winter loading. As presented previously, the pricing scheme is a crucial factor in the market operation and DER scheduling. This also affects network loss along the distribution feeder. Results show that the network losses are higher in SToU pricing than in flat pricing. It further deteriorates when LEM is introduced under the SToU pricing, primarily due to increased energy arbitrage through P2P transaction opportunities.

Voltage at PCC:

The voltage at the point of common connection (PCC) nodes connecting the customers to the network is an important performance metric for the distribution network. Fig. 8 illustrates the voltage distribution for the winter month for all the scenarios. It is clearly visible that the spread of the voltage profile for the SToU scenario is broader and thus deteriorates further than the flat scenario, especially on the under-voltage side. Fig. 8(b) shows that a considerable number of hours are experiencing under-voltage when LEM is implemented. In contrast, the voltage profile during the summer month, as presented in Fig. 9, experiences less spread, indicating the combination of rooftop PV and residential ES, appearing less impactful for high PV and low demand situations for both REM pricing schemes.

Table 3 quantifies the percentage of operating hours across the studied months when the voltage at the connecting nodes is experiencing under-voltage or over-voltage (±5%). It can be seen that the voltage problem is primarily concentrated on the under-voltage side rather than the over-voltage side. Including ES in the DER portfolio significantly reduces customers' simultaneous injection of PV electricity during the high PV generation hours. The ES allows customers to store energy for later self-consumption or P2P transactions. However, the over-voltage situation will rise with higher penetration of customers in the test feeder having

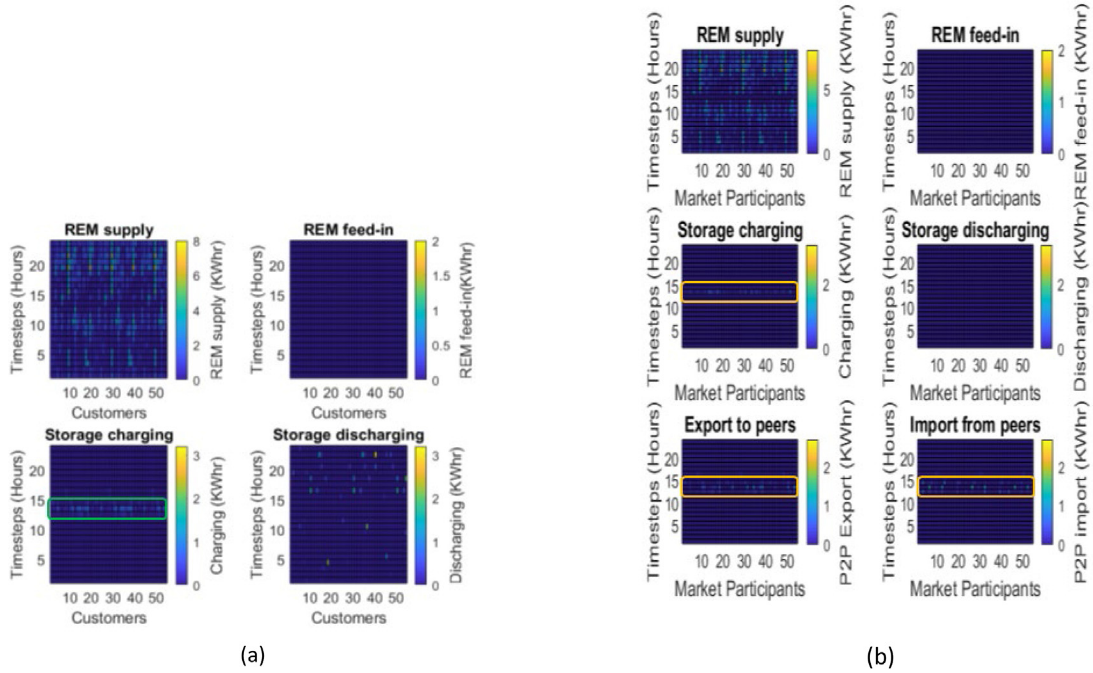


Fig. 4. REM interaction, ES operation and P2P transactions for both cases — (a) SO-Flat and (b) LEM-Flat on the winter day. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

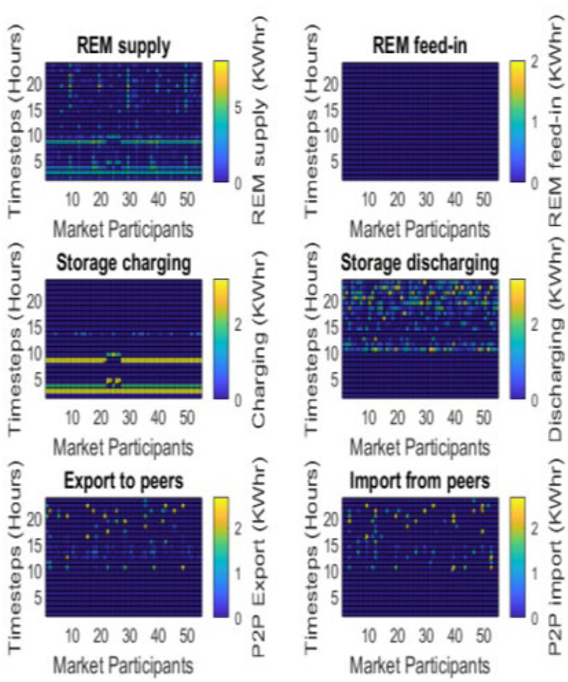
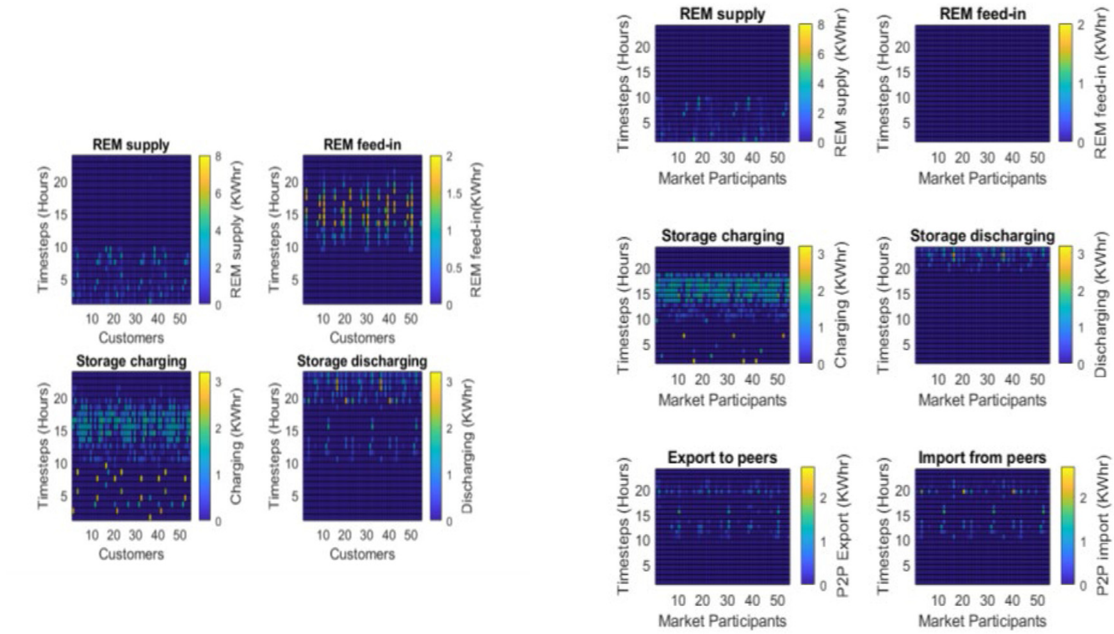


Fig. 5. REM interaction and P2P transactions for LEM-SToU case on the winter day.

only solar PV in their DER portfolio. The hours with the under-voltage situation have surged significantly when LEM operates under SToU pricing in the winter month. To further illustrate the customers' voltage profiles across time, Fig. 10(a) and (b) demonstrate the voltage profiles of all the customers for seven consecutive seven (7) days in the middle of the winter month. It indicates that the LEM under SToU pricing deteriorates the voltage profiles. Such a phenomenon occurs severely at low price hours and for the customers at the end of the network feeder (e.g. customers 35–37, 50, 52–53 and 55 in Fig. 2). This is because of the high charging of ES happening during the low price hours (as seen in Fig. 5) to avail the energy arbitrage opportunity through P2P transactions. Therefore, energy arbitrage is a critical factor in deteriorating voltage profiles. It can be further verified in Fig. 11, where LEM-Flat in winter week and LEM-SToU in summer week show the voltage profiles being better than LEM-SToU scenarios in winter week. This is because LEM-Flat in winter week does not have energy arbitrage due to the absence of differential tariffs. Similarly, the amount of energy arbitrage is also insignificant in the LEM-SToU scenario in the summer week as the high PV generation can meet the low demand of the energy community.

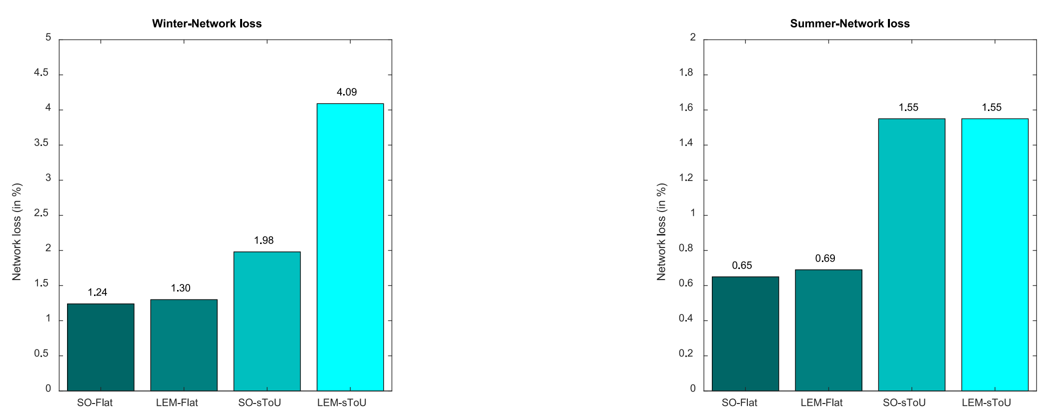
Three-phase voltage unbalance effect:

Another critical performance metric specifically crucial for the LVDN is the voltage unbalance occurring due to the unsymmetrical loading at the three phases in the network. It has several detrimental consequences, such as low performance of three-phase induction motors (Faiz et al., 2006), higher power losses etc. Therefore, it is imperative to investigate the impact of residential DER scheduling and especially the ES operation, governed by LEM or SO under different REM pricing schemes, on the voltage unbalance of the distribution network. Voltage unbalance can be evaluated in different ways (Pillay and Manyage, 2001). This paper presents the calculation of voltage unbalance in terms of IEEE's true definition; the percentage voltage unbalance factor (% VUF), defined as the ratio of the negative and positive sequence voltage components. The paper presents the critical scenarios discussed above rather than giving all the scenarios. Voltage unbalance becomes significant when customers show high energy exchange with REM. Fig. 12 illustrates SToU pricing scenarios for the typical winter day, demonstrating the maximum % VUF among all the scenarios reaching 0.6%–0.8% at certain hours. For both SO and LEM scenarios, %VUF is higher at night hours (high demand of winter night) and specific hours in the early morning (high ES charging driven by differential pricing). Voltage unbalance further augmented in the LEM-SToU scenario due to the energy arbitrage through P2P transactions.



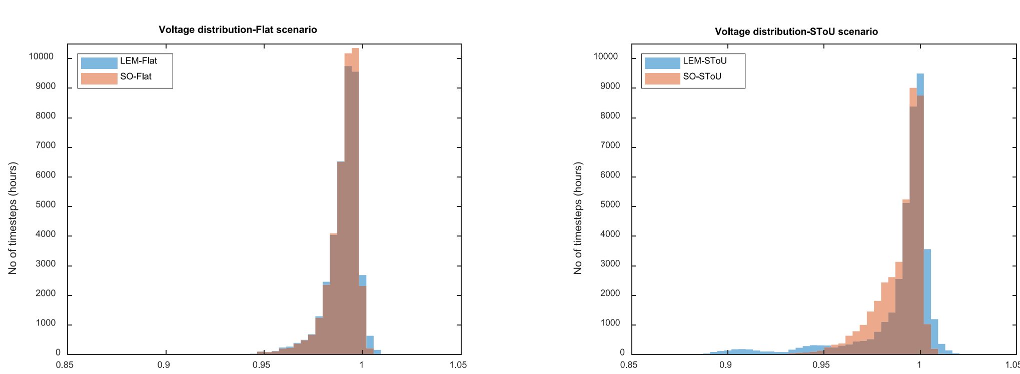
(a) (b)

Fig. 6. REM interaction and P2P transactions for both cases — (a) SO-SToU and (b) LEM-SToU on the summer day.



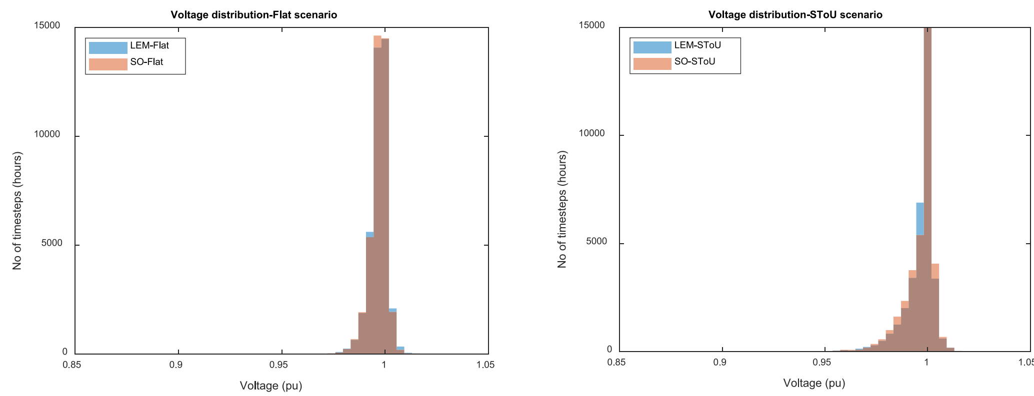
(a) (b)

Fig. 7. Network loss across different scenarios — (a) winter month, (b) summer month.



(a) (b)

Fig. 8. Voltage distribution in the winter month.

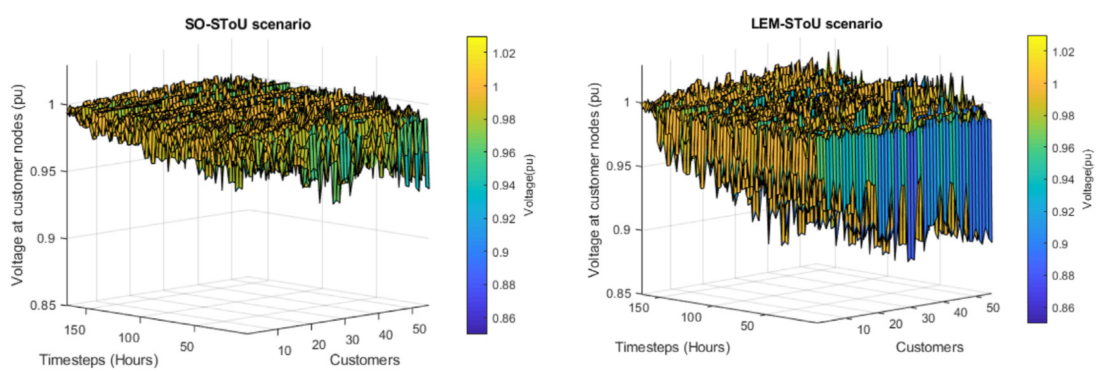


(a) (b)

Fig. 9. Voltage distribution in the summer month.

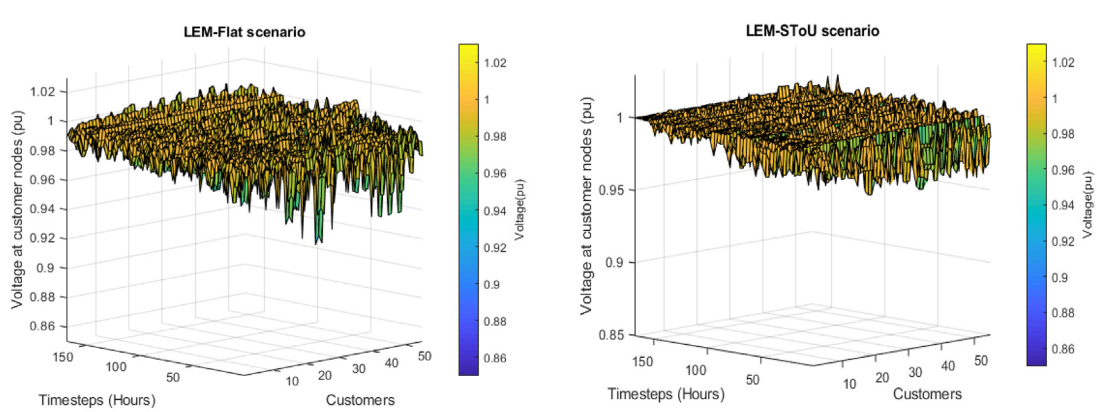
Table 3
Results on operating hours violating voltage thresholds.

	Summer		Winter	
	Under-voltage hours in % ($V < 0.95$ p.u.)	Over-voltage hours in % ($V > 1.05$ p.u.)	Under-voltage hours in % ($V < 0.95$ p.u.)	Over-voltage hours in % ($V > 1.05$ p.u.)
SO-Flat	0	0	0.38	0
SO-SToU	0.07	0	1.24	0
LEM-Flat	0	0	0.42	0
LEM -SToU	0.16	0	7.06	0



(a) (b)

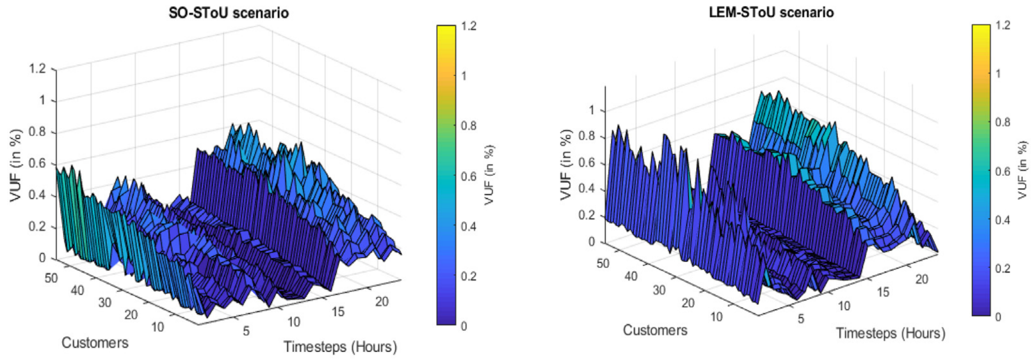
Fig. 10. Voltage profiles of all customer nodes for both SO-SToU and LEM-SToU scenarios in winter week.



(a) (b)

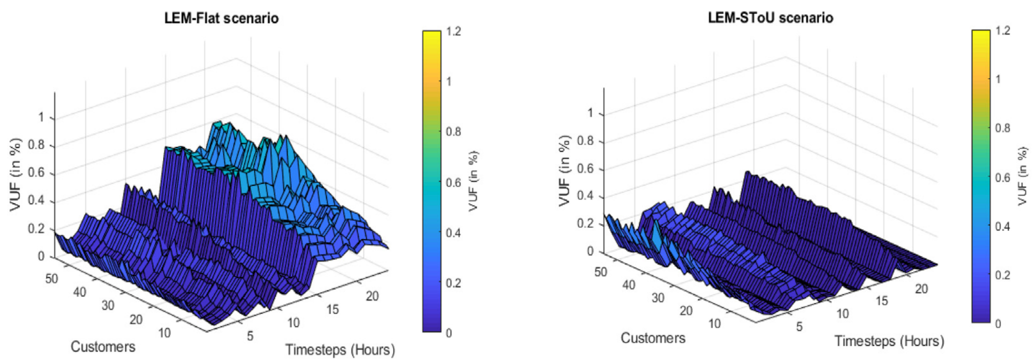
Fig. 11. Voltage profiles of all customer nodes for LEM-Flat in winter week and LEM-SToU in summer week.

In contrast, the flat pricing scheme in Fig. 13(a) shows that %VUF is high only at night. This is because the absence of differential pricing eliminates the high ES charging and corresponding high %VUF from 00:00 to 09:00. Therefore, the %VUF is also lower than the SToU pricing scheme. Furthermore, as shown in Fig. 13(b), the severity of voltage unbalance even lower on a



(a) (b)

Fig. 12. Voltage unbalance of all customer nodes for SO-SToU and LEM-SToU scenarios on a winter day.



(a) (b)

Fig. 13. Voltage unbalance of all customer nodes for (a) LEM-Flat scenario on a winter day and (b) LEM-SToU scenario on a summer day.

summer day. This is because it spreads across the day, dictated by the timing of PV generation and demand profile.

3.3.3. Key findings and recommendations

The extensive simulation studies suggest up to put forward the following findings and thus recommendations for the stakeholders and market actors:

- The combination of differential retail pricing under the SToU case and the feed-in tariff scheme has resulted in ES being utilised primarily for energy arbitrage, causing higher energy export to earn revenue through the feed-in tariff. This may also create a negative impact on the distribution network performance. Hence, this finding deserves special attention from the LEM policymaker, regulatory authority, and network operator in defining the LEM framework and regulations.
- Seeing the detrimental network performance of LVDN under specific scenarios, special attention is required from the distribution system/network operator (DSO/DNO) to avoid expensive network reinforcement. There is currently a range of non-wire alternatives on discussion, e.g. redesigning the distribution network tariff structure towards locational, capacity-based tariff (CEER, 2020a), DSO-level flexibility market (CEER, 2020b), etc. DSO needs to develop a suitable solution specific to residential customers in LVDN, even for any change in the network codes.
- Though the LEM appears like a beneficial, market-based approach for the energy community and residential customers, the trade-off necessary for the rest of the energy chain should be acknowledged to waive some benefits to reach an optimal, sustainable, sustainable solution for others.
- The introduction of LEM has resulted in a new phenomenon, e.g. energy arbitrage within the energy community and primarily due to the StoU pricing as indicated in this work, which has not been considered in the traditional business model of electricity retailers. Therefore, the retailers should revisit their business model to facilitate the LEM roll-out under the future REM structure.
- The regulatory framework for the energy community is still in a nascent stage, primarily focused on energy sharing and collective self-consumption (CEER, 2019). Therefore, policy and regulations on the energy community should address the findings for fostering the development of the LEM framework under the energy community paradigm, keeping in mind that LEM is one of the most promising consumer-centric, market-based approaches.

4. Conclusion

The smooth integration of LEM in the centralised wholesale electricity market (WEM) deserves a holistic understanding of how the exogenous retail electricity market (REM) pricing impacts the different constituents of LEM along with the LVDN hosting the LEM. This paper contributes to the discussion on REM pricing by investigating its economic benefit for the energy community and short-term operational effect on DER scheduling and LVDN performance in the presence of residential and distributed energy storage. The paper analyses the LEM and self-consumption (self-optimisation in the paper) scenarios under two existing REM pricing schemes in Ireland: flat pricing and sToU pricing. Results indicate that the LEM successfully maximises collective self-consumption and reduces the net supply cost of exchanged energy with REM. An interesting observation from the results is that the presence of residential ES under SToU pricing has opened the door to energy arbitrage. Hence, the ES imports energy at low price hours, stores it, and helps to meet the self-demand or sells it to other customers at high price hours in the energy community enabled by the P2P transactions. There is a strong correlation between the seasonal variation of demand and generation profiles with the P2P operation. P2P transaction is primarily dominated by energy arbitrage in winter and surplus solar PV in summer. However, the network unaware LEM operation under SToU pricing, which also constitutes the ES schedule, appears to be detrimental to the LVDN performance during the winter with a high volume of energy arbitrage. It results in higher network loss, frequent under-voltage conditions and an unbalanced network. We thus observe a trade-off between the economic benefit of the energy community and LVDN performance with the introduction of LEM under the existing REM structure.

Future work will incorporate the uncertainty of generation and consumption in modelling and investigate its consequences. Cyclic degradation of ES is another important factor while considering in the LEM operation and will be included to understand the more dynamic impact of ES. There are examples of spot market price-driven dynamic retail pricing implemented across countries. Further work will quantify the effects of such hourly (time granularity below hours) dynamic pricing on LEM operation along with the network performance study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work is partly supported by the BEYOND project, funded by the joint programming initiative ERA-Net Smart Energy Systems, co-funded by the European Union's Horizon 2020 research and innovation programme under grant agreement no 775970, Sustainable Energy Authority of Ireland - Grant Agreement 19/RDD/578 and IEA USER TCP task GO-P2P in IERC. The authors in IERC thankfully acknowledge the support from the Department of the Environment, Climate and Communications and the Sustainable Energy Authority of Ireland.

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