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Impact of Distributed Energy Resources in Smart Homes and Community-based Electricity Market

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Abstract— **The transformation of passive to energy-active consumers in smart homes has been enabled by the proliferation of distributed energy resources (DERs) and demand-side management technologies. Building a smart community-based electricity market (SCEM) centred around a local energy community has the potential to expedite this transformation by tapping the flexibility associated with peer-to-peer energy transactions inside the community. The paper presents a systematic approach to quantifying the benefits of smart homes, starting from the energy-passive to energy-active homes under SCEM with intermediate stages identifying smart homes with DERs. The investigation also includes the impact of seasonal variations with contrasting characteristics. Smart homes with solar PV and energy storage (ES) under SCEM achieve maximum savings of 50% and 36.6% for the summer and winter months, respectively, and SCEM boosts consumption of localised green energy by a further 31% in the summer month. ES leverages the smart homes gain significantly through self-consumption and energy arbitrage. However, the operation of ES under SCEM in the winter month reduces the network's voltage stability. The study is conducted based on real-life measurements from an energy community in Ireland. Recommendations are made further to boost the transition of smart homes toward the decarbonisation of smart grid networks.**

Index Terms— **Peer-to-peer, transactive energy, smart homes, distribution grid, energy community, local market, distributed energy resources.**

I. INTRODUCTION

Towards the achievement of decarbonised European smart grid network by 2050, the European Commission (EC) has given high importance to its “Clean Energy for all Europeans Package (CEP)” by empowering individuals and groups of consumers to participate in this energy transition. Such energy transition demands residential households to transform the energy-positive smart homes into energy-active smart homes, thus building a smart community. This transformation will expedite if the residential customers are provided with a better choice of supply, access to reliable energy prices, possibility to produce and sell their own electricity with increased transparency and better regulation for more involvement in the energy system and respond to the price signals [1]. Smart community-based electricity market (SCEM), centred around a local smart community, is an emerging and consumer-centric market approach that empowers consumers with smart homes to become more active through participation in the trading of green electricity among smart homes within the community or beyond. As Europe is rolling out smart electricity meters at a promising pace [2] along with widespread deployment of DERs and energy management systems [3], the above-mentioned trend is becoming more eminent in future.

Currently, residential households only engage in the retail electricity market (REM), where consumers have long-term contracts with electricity retailers. The business model of REM is designed for traditional energy-passive residential households [4]. The energy transition is motivating to maximise self-sufficiency and minimise energy expenditure. The business model, which facilitates homes with DERs, involves energy retailers buying surplus electricity through support schemes, e.g. feed-in-tariff or net metering [5]. These support schemes have been successful in the rapid integration of DERs. Nevertheless, support schemes do not have any connection to the market price. As a result, it risks being market inefficient and burdened with a cost that is socialised across end users’ electricity bills. Over the last decade, the remuneration under such support schemes has been drastically reduced or terminated in most countries worldwide [6]. As subsidy-based support schemes are seeing a limited future, the subsequent progression of the energy-passive households towards energy-active smart homes with the inclusion of technologies, such as home energy management system (HEMS), energy storage system (ESS) etc., enabling demand-side management (DSM). This reduces smart homes’ electricity bills by maximising the self-consumption of locally generated electricity. Smart homes with DSM capabilities (such as peak shaving, shifting etc.) still operate under retail pricing structures. Though the feed-in of surplus energy is reduced with DSM in place, it still introduces cost recovery problems and cross-subsidisation among smart passive homes [7] [8]. This leads to the benefit of smart homes with DSM and DERs, depending on various factors, including self-consumption policy, retail tariff design and cost-recovery design of distribution networks [9]. SCEM is an advanced approach to extend the periphery of self-consumption to the community scale where smart homes engage in energy trading inside a community-based electricity market, minimising the supply from REM. This results in economic benefits for smart homes as local, peer-to-peer (P2P) transactions inside SCEM offer better pricing for buyers and sellers than energy retailers. This bottom-up, community-centred approach of SCEM provides market power to residential customers and facilitates rapid uptake of DERs in residential households. Apart from empowering residential customers, SCEM offers a coordinated, granular, market-based mechanism for smart community promoting local balancing of generation and consumption close to real-time. This introduces a decline in renewable curtailment, less usage of transmission networks, and other positive notions toward a decarbonised energy system [10].

Authors in [11, 12, 13, 14] have investigated the different types of DER assets, influencing the benefits of smart homes from a techno-economic perspective. The retail pricing scheme leverages the smart homes' benefits and [15] provides a comparative study of five tariff structures for four combinations of DER assets. [16, 17, 18] worked with different solution techniques for DER scheduling, e.g. mixed-integer linear programming, dynamic programming, and particle swarm optimisation. Recently, several research works have been conducted on the community-based electricity market with an emphasis on a range of aspects of the market design: market clearing mechanism, bidding strategy, and interaction with the wholesale market. Authors in [19, 20, 21, 22, 23] have worked on different market-clearing mechanisms having centralised and decentralised approaches and present the impact of such clearing mechanisms on the community along with other metrics such as scalability, the convergence of the local market. Another important aspect of the community-based market is the strategic and non-strategic bidding of the market players which have been studied in [24, 25, 26, 27]. The stochastic nature of DERs, being one of the key features of DERs, has been incorporated into the study of community-based electricity markets using two different broad approaches, e.g. robust optimisation [28] and stochastic programming [29] [30]. The data-driven approach is gaining attention in the scenario generation of stochastic programming [30]. A segment of literature on the community-based electricity market is often oblivious to the electricity network hosting the community. However, the network constraints must be respected with a certain degree of freedom. Electricity network constraints have been incorporated in this market formulation implementing a range of techniques, AC optimal power flow [31] [32], linearized DC optimal power flow [33] [34], network loss [35] [36], constraint-based sensitivity factors [37] and decoupled approach [38], [39], [40], [41] and studied the impact of network constraints on market outcome.

The research work related to the energy-passive homes' transformation to energy-active ones and the community-based electricity market found in the previously published articles; the authors observed a lack of comprehensive study which evaluates the benefits of the residential households under SCEM with a comparison of different transitional stages of an energy-passive home. The stages are identified as the gradual incorporation of DER assets. Several studies have investigated case studies of SCEM for different categories of DER assets. However, those studies present the finding from a community perspective. On the other hand, the studies under DER and DSM integration on residential households have paid attention from a techno-economical viewpoint with a limited focus on the operational perspective and their collective impact on the distribution network. Therefore, an integrated study is required to build synergy among different elements contributing to the benefits of energy-active smart homes under SCEM and the network performance. Detailed examination of these synergies is of paramount importance for fostering a smart community from conception to realisation, promoting the proliferation of energy-active smart homes. The novel contribution of the study are enumerated as follows:

- The paper presents the SCEM as a simplified and deterministic linear programming optimisation model, including realistic energy storage constraints and P2P transactions. The performance quality of this holistic approach is preserved by implementing the market and network model in a cascaded and decoupled fashion. This accommodates a high volume of data for seasonal study with significantly reduced computational time.
- A systematic approach is then presented to analyse the benefits of smart homes, starting from the initial stage of energy-passive homes towards energy-active homes under SCEM with intermediate steps identifying smart homes with DER assets (mainly PV and ES).
- A comparative study on different stages has been conducted on energy-passive and active smart homes for a short-term operational timeframe extending from hours to a month. It provides insights into different constituents working under the SCEM from an operational horizon.
- Power-flow-based quantitative assessment has also been carried out on a realistic low-voltage distribution network (LVDN) hosting the smart community.
- The impact of the time-of-use (ToU) tariff on the operation of ES is investigated, and thus, its impact on the HEMS and SCEM operations and the performance of LVDN is examined.
- The seasonal variations (summer and winter) with maximum load demand and clean energy generation conditions are analysed further to understand the possible extreme impacts of this energy transition at the community level.

The rest of the paper is organised as follows: the business model of SCEM in Section II. Section III presents the modelling approach of HEMS and SCEM along with LVDN details. Case studies and descriptions of the scenarios have been presented in Section IV. Section V discusses and analyses the results. Finally, Section V presents the conclusion of this work and provides future research directions.

II. BUSINESS MODEL

The development of innovative business models is of paramount importance to rolling out smart homes with DERs. Future smart grid networks will possess complex architecture with the presence of stochastic behaviour of DERs and the entrance of new actors in the energy transition. Business models require to ensure that value propositions for smart homes, utility suppliers, network operators, and other relevant stakeholders are well maintained. The definition of a business model is still changing to accommodate the rapid innovation undergoing in businesses. A short and concise definition of a business model in [42] is **"A business model describes how you create, distribute and capture value".**

The challenges of introducing an innovative business model in the energy system lie in effectively capturing value propositions for different actors and defining those complex values in the current environment. [43] has investigated the business model for prosumers in the UK and classified the business model into seven archetypes. The authors have taken the insights of those models in the paper to develop a business model for smart homes under SCEM with different DER portfolios.

The focal point of this study is on smart homes with residential electricity end-users. The SCEM introduces smart homes with the possibility to conduct P2P transactions within the local energy community sphere. It is motivated to boost the community's collective self-consumption, reducing dependency on REM electricity purchases. The presence of REM is necessary for the business model to ensure the security of supply. It is obvious that the smart homes under SCEM will not have collective energy self-sufficiency for each trading period on the operational horizon. Therefore, it requires a provision to transact deficit/surplus electricity with the central electricity market as it has not been utilised in the P2P transaction in SCEM. The role of the balance responsible party also needs to be addressed. The above-mentioned reasons persuade the presence of electricity retailers in the business case, with REM being the point of connection for SCEM to the central electricity market. The other key actors are the SCEM operator and distribution system operator (DSO). The role of the SCEM operator involves managing the P2P transactions among the market participants to reach the goal of the SCEM. Market participants in the SCEM are the electricity customers: producers, prosumers and consumers. DSO ensures the P2P transactions in the SCEM operation adhere to the network's technical constraints.

As defined by [44], four basic components constitute the business model: value proposition, customer interface, supply chain and financial model. Table I elaborates on the components under the framework of the business model proposed in the paper, especially from the perspective of smart homes and the SCEM operator.

TABLE I BUSINESS MODEL FRAMEWORK

Description of a business model framework
Value proposition: Smart homes under SCEM have several value streams. SCEM provides the provision of P2P transactions of electricity to other homes residing under the same SCEM. Therefore, smart homes can sell surplus energy to other peers. Smart homes with storage use differential pricing in the REM (ToU tariff) across time to perform energy arbitrage. Besides, SCEM has a provision to sell electricity to REM with a feed-in tariff. To make the SCEM business model lucrative for electricity customers, the P2P transaction price is assumed to be bounded by the ToU tariff and feed-in tariff. The buyers buy the P2P electricity in SCEM at a lower price than the ToU tariff, and sellers sell P2P electricity at a higher price than a feed-in tariff.
Customer interface: SCEM operator has contracts with smart homes, hosting DER assets, determining the sharing of income earned through different revenue streams. The contract also provides the DER assets' operation strategy, defining how the inelastic demand for smart homes under SCEM is sourced from the lower price of electricity. Therefore, the operational strategy is a multi-period optimisation problem scheduling the flexible DER assets to deliver low-price electricity to smart homes through the utilisation of flexibility of flexible DERs and P2P transactions within SCEM.
Supply chain: Smart homes having DER assets are the primary basis of SCEM. Smart homes with PV and residential ES have a higher advantage as they have a source of flexibility, opening up additional revenue streams. The model is based on a contractual agreement between smart homes and the SCEM operator. SCEM operators will have the direct control provision over flexible DER assets to schedule the operation. Remote metering and control equipment and information and communication technology (ICT) facilities are installed to monitor and manage the DER assets. PV generation and demand forecasting are the key aspects of the business model.
Financial model: A capital cost is involved in setting up the SCEM. Remote metering and control equipment, ICT infrastructure and DER facilities are the main sources of expenditure. The SCEM operator and smart homes cover the capital cost from revenue earned from different value streams. Smart homes can pay a membership fee, and the contractual agreement outlines revenue sharing. Smart homes with different DER assets can have different fees and contracts in place.

III. MODELLING APPROACH

The modelling approach presented in the paper is a two-stage, cascaded approach where the model of the study is comprised of two models: the HEMS/SCEM model and the LVDN model. The former model schedules the smart homes' flexible DER assets to meet the scenarios' defined objective (elaborated in Section IV-C). HEMS/SCEM model has two scheduling modes: HEMS and SCEM, to capture the business model of the study. The HEMS mode only schedules flexible DER assets of individual smart homes separately without providing P2P transactions. In contrast, the SCEM mode schedules the flexible DER assets based on the objective of the market having provision of P2P transactions among smart homes. This paper considers that only one of the modes under HEMS/SCEM is in operation, and residential ES is the only flexible DER asset modelled in the HEMS/SCEM. The second model features the network topology and characteristics of the network assets describing the distribution test feeder hosting the smart homes under SCEM. It synthesises its input dataset from the output of the HEMS/SCEM model and conducts network performance analysis based on the dispatch of the DER assets under HEMS/SCEM. The two-stage, cascaded modelling approach enables the extraction of outcomes from the two models separately, namely dispatch outcome from network-unrestrained HEMS/SCEM model and network performance outcome from LVDN model, which is useful for the study. Two different software platforms have been used for the separate models. HEMS/SCEM model is developed in the MATLAB environment using open-source optimisation modelling language, YALMIP and MOSEK being the optimisation solver. LVDN model is developed in Open Source Distribution System Simulator (OpenDSS), which can conduct a time-series simulation of the complex, unbalanced, multi-phase distribution network. Further details on the modelling approach, HEMS/SCEM model and LVDN model can be found in the authors' previous work [45]. This paper's HEMS/SCEM model follows a similar methodological approach as presented in [41] and [19]. However, the contribution of the paper is not in terms of methodology, rather the quantitative, comprehensive analysis of benefits brought by SCEM to residential smart homes compared with other transitional stages.

A. HEMS/SCEM Model

The HEMS/SCEM model is a linear multi-period optimisation model that has been formulated for a set of smart homes, $\mathcal{P} = \{1,2,\ldots\ldots,N_p\}$ across a market horizon with a trading period denoted by $t \in T$ having duration, ΔT. Both modes of the HEMS/SCEM model are formulated to minimise the procurement cost of electricity and to maximise the revenue from exporting energy to the electricity retailer. The objective function of the HEMS model (equation (1)) is centred around each smart home separately and individually, whereas the SCEM model (equation (2)) operates for the entire smart community collectively with the provision of P2P transactions.

HEMS mode

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

s.t. energy balance constraint
DER operational constraint

SCEM mode

$$\underset{P_{p,t}^{Im},P_{p,t}^{Ex}}{\text{Min}} \sum_{t} \left(\sum_{p} \lambda_t^{Im} P_{p,t}^{Im} - \sum_{p} \lambda_t^{Ex} P_{p,t}^{Ex} \right)\Delta T \tag{2}$$

s.t. energy balance constraint
DER operational constraints
P2P transaction constraint

where, λ_t^{Im} is the ToU retail electricity tariff, λ_t^{Ex} is the feed-in tariff, $P_{p,t}^{Im}$ represents the amount of electricity procured from the retailer and $P_{p,t}^{Ex}$ represents electricity sold to the retailer. The first term of the objective function represents the cost function related to procuring electricity from REM under a ToU tariff scheme. The second term refers to the revenue function denoting electricity exported to the grid at a feed-in-tariff rate. The constraints of the HEMS/SCEM model are elaborated below:

Energy balance constraint

$$P_{p,t}^{Im} + \sum_{q\neq p} P_{q\rightarrow p,t}^{P2P\ buy} + P_{p,t}^{dis} + P_{p,t}^{gen} = P_{p,t}^{Ex} + \mu^{loss} \sum_{q\neq p} P_{p\rightarrow q,t}^{P2P\ sell} + P_{p,t}^{ch} + P_{p,t}^{dem} \tag{3}$$

Equation (3) refers to the energy balance constraint for each smart home operating under HEMS or SCEM mode. Here, superscript *ch* and *dis* are used to represent charging and discharging of the residential ES, whereas, $P_{p,t}^{dem}$ and $P_{p,t}^{gen}$ indicate the load and self-generated electricity of smart homes, $p \in \mathcal{P}$ during the trading period, $t \in T$. The terms associated with $P_{q\rightarrow p,t}^{P2P\ buy}$ and $P_{p\rightarrow q,t}^{P2P\ sell}$ Equation (3) only applies to the SCEM mode but not to the HEMS mode. $P_{q\rightarrow p,t}^{P2P\ buy}$ represents the electricity procured by smart home p from peer q in the SCEM and $P_{p\rightarrow q,t}^{P2P\ sell}$ represents vice-versa. μ^{loss} is a co-efficient denoting network loss factor affiliated with P2P transactions.

P2P transaction constraint

$$\sum_{p}\sum_{q\neq p} P_{q\rightarrow p,t}^{P2P\ buy} = \mu^{loss} \sum_{p}\sum_{q\neq p} P_{p\rightarrow q,t}^{P2P\ sell} \tag{4}$$

Equation (4) ensures the total electricity purchased through P2P transactions should be equal to electricity sold in P2P transactions at each trading period $t \in T$.

DER operational constraints

This paper considers only residential ES as a flexible DER asset and thus, requires to be represented in the optimisation modelling. The operational constraints of the residential ES can be expressed as:

$$P_{p,t}^{ch} \leq P_p^{ch,max} \tag{4}$$

$$P_{p,t}^{dis} \leq P_p^{dis,max} \tag{5}$$

$$\underline{E_p} \leq E_{p,t} \leq \overline{E_p} \tag{6}$$

Equations (4) and (5) enforce upper limit constraints to charging power, $P_{p,t}^{ch}$ and discharging power, $P_{p,t}^{dis}$ of residential ES. Equation (6) presents the constraint on state-of-charge, $E_{p,t}$ of ES units with upper, $\overline{E_p}$ and lower-level, $\underline{E_p}$ threshold. Lastly, the state-of-charge dynamics of ES is expressed by the following constraint,

$$E_{p,t} = E_{p,t-1} + \eta_p^{ch} P_{p,t}^{ch} \Delta T - P_{p,t}^{dis} \left(\frac{1}{\eta_p^{dis}}\right) \Delta T \tag{7}$$

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

B. LVDN Model

LVDN model is capable to conduct detailed network studies, e.g. power flow solution, fault calculation, harmonic analysis. It takes power injection profiles of each smart home in the LVDN, which is calculated by equation (8) and runs the power flow. Different power flow solution algorithms exist to solve power flow for distribution networks [46], however, this paper uses the default built-in power flow solution algorithm in OpenDSS [47].

$$P_{p,t}^{inj} = P_{p,t}^{Im} + \sum_{q\neq p} P_{q\rightarrow p,t}^{P2P\ buy} - P_{p,t}^{Ex} - \sum_{q\neq p} P_{p\rightarrow q,t}^{P2P\ sell} \tag{8}$$

where, $P_{q\rightarrow p,t}^{P2P\ buy}$ represents the electricity procured by smart home p from peer q in the SCEM and $P_{p\rightarrow q,t}^{P2P\ sell}$ represents vice-versa. These two terms in equation (8) have only been considered in the SCEM mode but not in the HEMS mode.

IV. SYSTEM SETUP

A. *Case study*

The case study is presented for a real neighbourhood located in the Dingle area in Ireland [48]. The smart home's time series measured smart meter data has been used. DER assets considered in the study are roof-top solar PV and residential ES. The capacities of the roof-top PV of the smart homes are ranged between 2.0-2.2 kWp. The lithium-ion battery is considered a residential ES with a capacity of 10kWh/3.3kW peak. Data of 55 smart homes are used for two different months: January (winter) and June (summer) 2020, to understand the impact of seasonal variation in the best and worst conditions. The community self-sufficiency of the neighbourhood, defined as a percentage ratio of aggregated solar PV generation and aggregated consumption for the neighbourhood, for above mentioned months is 12.6% and 62.5%, respectively. As described in Section III-A, the HEMS/SCEM model takes day-night electricity retail prices as an exogenous price signal from the existent static ToU tariff schemes from REM in Ireland. The day and night rates are 20.07 c€/kWhr and 9.91 c€/kWhr, respectively, for 2020. The feed-in tariff has a fixed rate of 9.0 c€/kWhr. The DER scheduling and P2P trading in HEMS/SCEM model is considered to operate in hourly resolution.

B. *Test network*

The IEEE European low voltage test feeder has been used as an LVDN test network for the study. It has the radial topology, a typical European low voltage distribution network. The study uses a modified version of the test feeder with a 200 kVA, 11 KV/0.416 kV transformer to align the parameters with the Irish network. The test feeder consists of 906 buses and 55 customer connection points for single-phase residential customers. All of the 55 smart homes are located at different connection points. The smart homes are modelled as constant PQ loads. The power flow simulation uses the connection point at MV/LV substation as a slack bus. In alignment with the temporal resolution of the HEMS/SCEM model, the power flow has also been conducted on hourly resolution. Fig. 1 shows the LVDN test feeder's schematic diagram with the smart homes' placement.

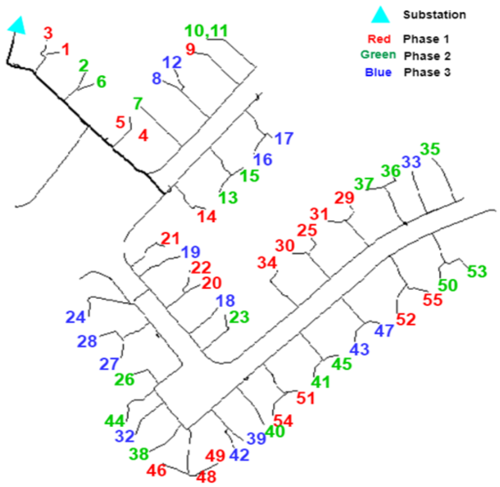

Fig. 1 Schematic diagram of test network identifying location of smart homes.

C. *Scenarios' descriptions*

The scenarios have been developed considering the notion of the paper to show the benefits of DER assets and SCEM on smart homes. Therefore, the proposed scenarios consider the gradual integration of DER assets and P2P trading provision to a passive home. Five scenarios have been evaluated for the study described in detail in Table II.

TABLE II DESCRIPTION OF SCENARIOS IN THE STUDY

Description of scenarios
(a) Passive home (*Base*): This scenario serves as the benchmark, with all the homes being considered passive homes with no DER assets, hence pure consumer. There is no provision for P2P trading as SCEM has not been established. The entire demand of the house is met by REM-supplied energy.
(b) Home with PV only (*Base+PV*): Each smart home is only equipped with roof-top solar PV. PV generation is utilised for self-consumption, and any surplus electricity is exchanged with the retailer as per the REM tariff scheme.
(c) HEMS with PV and ES (*HEMS-PV+ES*): Smart homes with residential on-site ES and roof-top solar PV operated by (home energy management system) HEMS mode (elaborated in Section III-A). However, SCEM does not exist yet and, therefore, has no provision for P2P trading.
(d) SCEM with PV only (*SCEM-PV*): SCEM has been established as described under SCEM mode in Section III-A. Smart homes have the provision of P2P trading, and all homes are equipped with roof-top solar PV. This scenario has not considered any residential ES and therefore does not possess DER flexibility. Through P2P transactions, these smart homes can purchase/receive surplus PV electricity from other active smart homes in the community.
(e) SCEM with PV and ES only (*SCEM-PV+ES*): This scenario demonstrates the highest level of activism/flexibility among all scenarios where smart homes have residential on-site ES and roof-top solar PV. The scenario considers the arrangement to engage in P2P trading in operation.

Under each scenario, every smart home's DER asset portfolio is considered identical. Consequently, the smart homes' consumption and generation profiles have been assumed consistent across all the cases.

V. SIMULATION RESULTS

Extensive simulation studies have been performed for all the scenarios, along with network performance analysis. In addition, hourly time series data have been implemented for the selected months.

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A. Exchange with the energy retailer

To understand the extreme impact of the different scenarios on smart homes DER scheduling and subsequently their interaction with REM, Fig. 2 illustrates the average net supply of electricity for all the scenarios for January 16, 2020, the day with a maximum aggregated demand in the representative winter month. Net supply is calculated by subtracting the smart home's sold energy from the procured energy for each market time interval. Since PV generation is low compared to the demand in the winter month, scenarios with no ES (Base, Base+PV and SCEM-PV) do not show any significant change in net energy supply. However, the scenarios with ES (HEMS-PV+ES and SCEM-PV+ES) have shifted in the net supply of energy across the day where most of the energy is now consumed in the low tariff hours (from midnight to hour 09:00). The base scenario (average demand profile of smart homes) has two peaks, with the morning peak occurring at 10:00 and the evening peak at 19:00. With the introduction of ES (HEMS-PV+ES and SCEM-PV+ES), smart homes have the flexibility of shifting their consumption; hence, the peak of the day occurs at 09:00, the last hour of the low tariff time band. It can be observed that compared to HEMS-PV+ES, SCEM-PV+ES has further increased net supplied energy in the low tariff hours timeband and reduced consumption in the high tariff hours. This is due to the energy exchange/P2P transaction provision opening up the energy arbitrage with neighbouring smart homes.

In continuation, Fig. 3 depicts the net supply of June 21, 2020, the day with a maximum aggregated PV generation for the summer month. High PV generation in the summer month diminishes the need for net supply energy from REM during the mid-day for all the scenarios with solar PV. It can be seen that the Base+PV and SCEM-PV scenarios have high feed-in as smart homes do not have the flexibility to store excess energy.

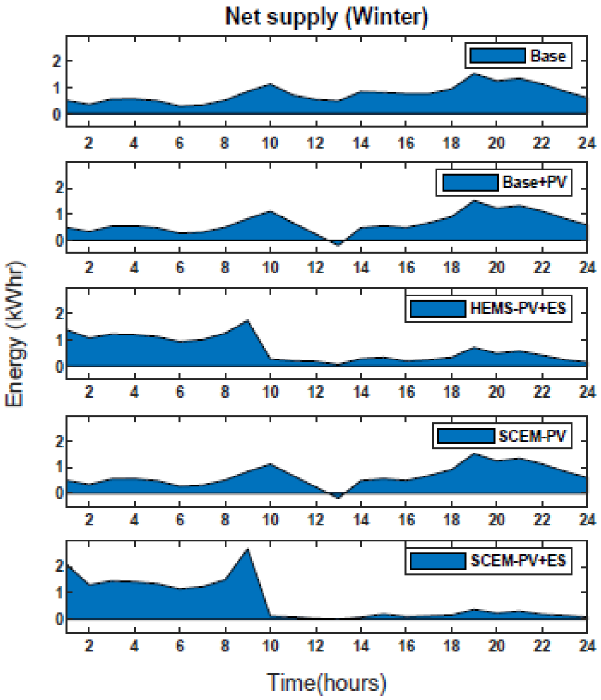

Fig. 2 Net supply profiles for all scenarios for the day with maximum demand in winter day.

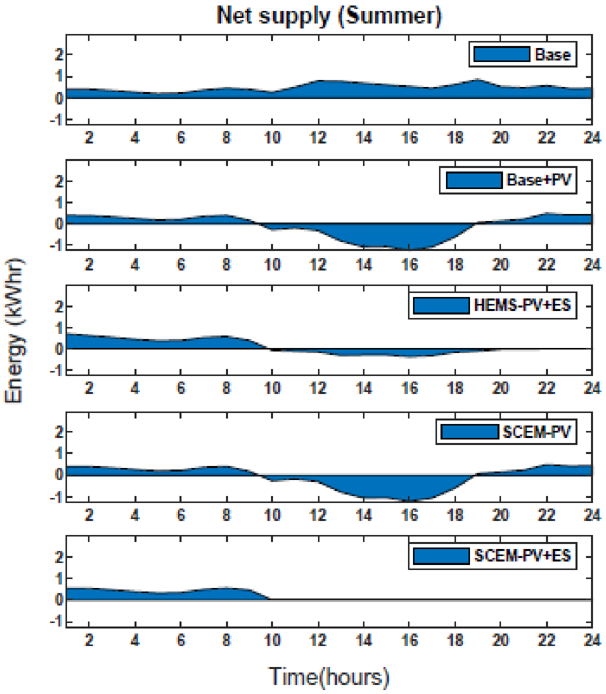

Fig. 3 Net supply profiles for all scenarios for the day with maximum PV generation in summer day.

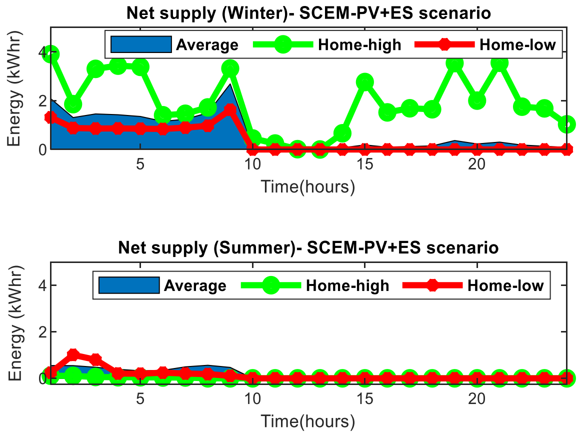

Fig. 4 Net supply profiles of two individual smart homes along with averaged profile for the community (SCEM-PV+ES scenario).

Since all the smart homes have PV facilities with nearly the same capacity and due to the high PV generation during the mid-day, the homes achieve self-sufficiency. The possible P2P trading/energy exchange options are also nearly zero. Hence, the SCEM-PV scenario does not show any reduction in the feed-in energy.

With the introduction of ES (HEMS-PV+ES and SCEM-PV+ES), the stored PV energy has also covered the net REM supplied energy required in Base+PV and SCEM-PV scenarios. Moreover, the SCEM-PV+ES scenario has demonstrated the highest performance with no energy exchange with the retailer after the low tariff time band as smart homes with energy deficit at certain hours meets their demand from other peers with excess energy through the P2P trading.

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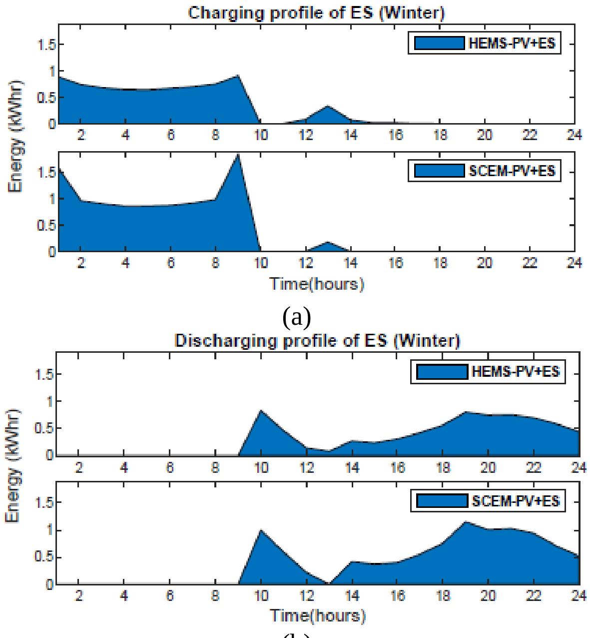
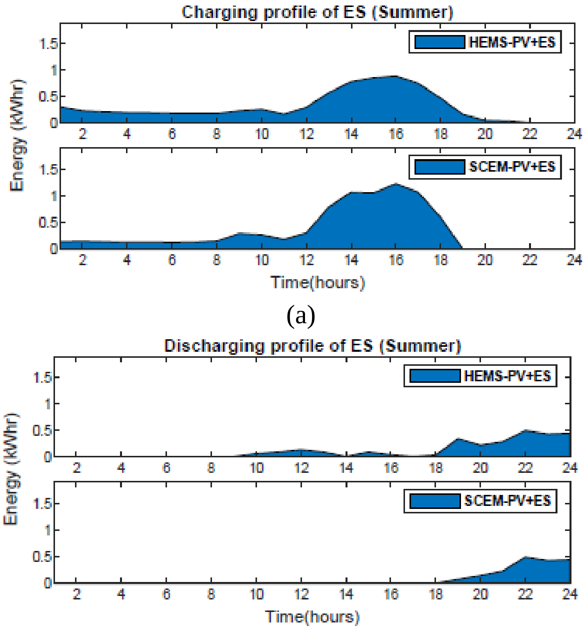


(a)

(b)

Fig. 5 Averaged (a) charging and (b) discharging profile of the smart homes for the winter day.



(a)

(b)

Fig. 6 Averaged (a) charging and (b) discharging profile of the smart homes for the summer day.

Though Fig. 2 and 3 show the average value of the net supply, it is also important to observe the extreme net supply conditions of smart homes. Hence, the net supply profile of the individual smart homes with the highest and lowest values in comparison to averaged profile for both winter and summer days are presented in Fig. 4. This is presented for the most prospective scenario for the smart community with greater flexibility, SCEM-PV+ES. For the winter day, the smart homes with the highest and lowest-demand are considered, whereas, for the summer day, smart homes with maximum and minimum PV generation are shown.

B. Operation of ES

As observed in the previous Section V-A, the flexibility introduced by the ES plays a crucial role in the operation of smart homes to achieve the objective set by the scenario. Fig. 5 shows the charging and discharging profile of the ES averaged over all the smart homes on a winter day. It can be seen that the charging is occurred primarily at a low tariff timeband, up to hour 10:00. SCEM-PV+ES scenario observes more charging at low tariff hours compared with the HEMS-PV+ES scenario. This is due to the fact the winter day has low PV generation and high demand. As a result, smart homes involve in charging ES facilities procuring electricity from REM at low tariff hours to meet the demand for the rest of the day. Since SCEM provides energy exchange/trading possibility, this creates an opportunity for smart homes to engage in energy arbitrage, procuring electricity from REM at low tariff hours and selling it under SCEM at a lower price to other smart homes with energy deficits during the high tariff hours. This observation is also coherent with Fig. 2, where a similar pattern is observed over low tariff hours, but the net supply is reduced in high tariff hours. Though energy arbitrage boosted by P2P trading brings benefits to the smart homes under SCEM, it results in higher charging peaks in different time horizons, which is detrimental to the distribution network. It needs to be noted that the figures shown in Fig. 5 is average profile and therefore, charging profiles of a number of smart homes will be higher than that which deteriorates the voltage of the network nodes connecting these smart homes. The averaged discharging profile shown in Fig. 5 indicates the discharging of ES is taking place to cover the demand of smart homes at high tariff hours or excess PV generation (hours 12:00- 14:00) to reduce the bills. In the summer month, the charging action is primarily from excess PV energy to cover the demand avoiding procurement from the REM. It can be seen in Fig. 6 that significant charging action is taking place at mid-day which is later discharged to meet the demand after hours 19:00. In contrast to the HEMS-PV+ES scenario, SCEM-PV+ES observes lower ES charging at low tariff hours and higher ES charging during mid-day. As the HEMS-PV+ES scenario does not serve P2P trading, smart homes, with their ES being charged to full capacity from excess PV energy, exports the surplus PV generated electricity to the retailer (as seen in Fig. 3). On the contrary, the P2P trading arrangement in the SCEM-PV+ES scenario allows smart homes to trade PV generated electricity with their peers in need of energy resulting in higher community self-sufficiency. Hence,

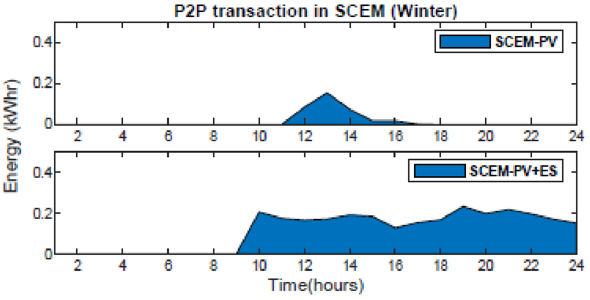


Fig. 7 Averaged P2P transaction profile of the smart homes for the winter day.

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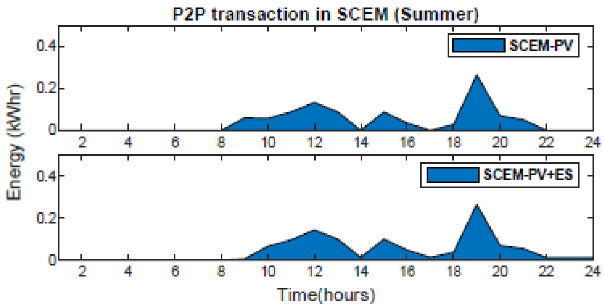


Fig. 8 Averaged P2P transaction profile of the smart homes for the summer day.

electricity feed-in to the energy retailer diminishes at high tariff hours for SCEM-PV+ES scenario in Fig. 3 and similarly, discharging is not taken place at mid-day in Fig. 6.

C. *P2P transactions*

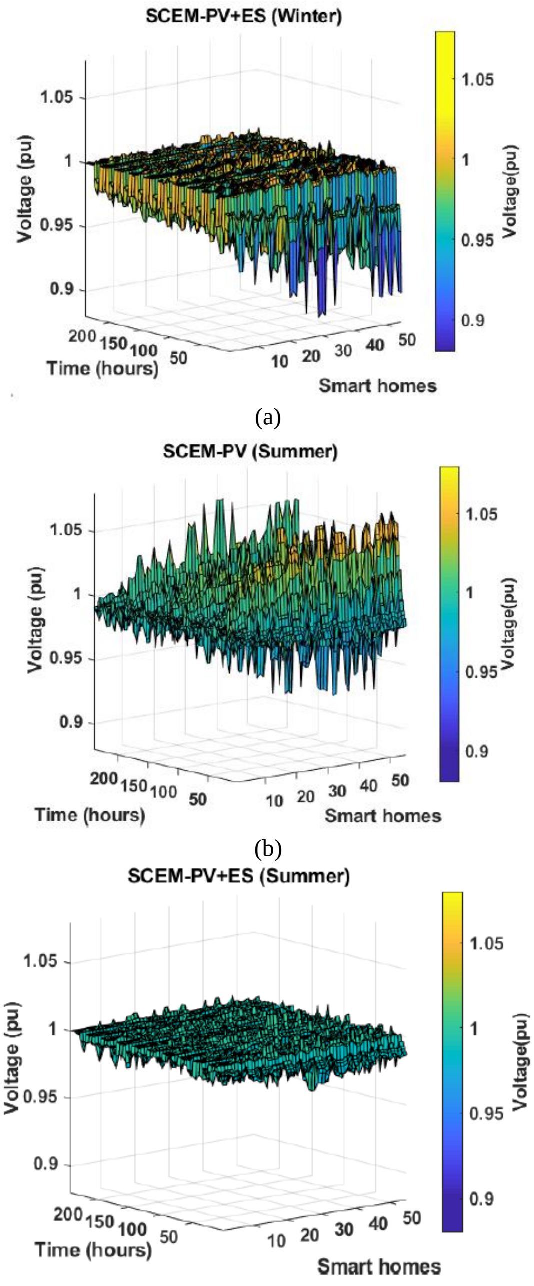
P2P transactions can be considered as an indication to assess the factors impacting SCEM operation. Different DER assets under two scenarios, SCEM-PV and SCEM-PV+ES, give insights into the role of ES on SCEM operation. In Fig. 7, for the winter month, the contrast between the two scenarios implies that the P2P transactions are mostly contributed from the energy arbitrage. The SCEM-PV scenario has P2P transactions only for a few hours at mid-day when smart homes with surplus PV trades it with their peers. The smart homes, equipped with ES, store their surplus PV for later use rather than selling it to other peers under SCEM or exporting it to the REM (Fig. 3, HEMS-PV+ES scenario). Besides, ES opens up the prospect of energy arbitrage and thus, contributes to significant P2P transactions and is initiated just after the low tariff time band (after hour 09:00). This demonstrates the consolidated impact of ES and ToU tariff on P2P transactions, especially at times when community self-sufficiency is low. On the other hand, the P2P transaction is driven by surplus PV generation with insignificant energy arbitrage for days with high community self-sufficiency, as seen in Fig. 8 for a summer day. Therefore, both scenarios are closely alike.

D. *Smart home's benefit*

The results have been presented in previous sections as averaged profiles of smart homes for representative winter and summer days. Table III summarises the monthly average values of the selected parameters for the smart homes under the five scenarios given in Table II. It can be seen that, compared to the *Base+PV* (b) scenario, the *SCEM-PV+ES* (e) scenario has the maximum reduction in net supply cost with 36.6% and 50% (marked in blue) for winter and summer month respectively. With the introduction of ES in the smart homes' portfolio {*HEMS-PV+ES* (c) and *SCEM-PV+ES* (e)}, the localised consumption of locally generated electricity, usually green energy in nature, is maximised as indicated by the reduction of REM exported energy for smart homes in the summer month (marked in green) compared with scenario (b) (91 kWhr) with homes having only PV, but no ES. The impact of P2P energy exchange provision on smart homes' consumption of green energy is visible in the summer month (month with higher community self-sufficiency), which exhibits a reduction of

TABLE III MONTHLY AVERAGED RESULTS OF A SMART HOME UNDER DIFFERENT SCENARIOS

	Winter					Summer				
	a	**b**	**c**	**d**	**e**	**a**	**b**	**c**	**d**	**e**
Net supply cost (€)	80	71	52	69	45	57	26	15	23	13
REM export (kWhr)	0	19	1	6	0	0	91	27	62	1
P2P (kWhr)	0	0	0	13	75	0	0	0	29	35



(a)

(b)

(c)

Fig. 9 Voltage profiles of the nodes connecting smart homes for scenarios - (a) SCEM-PV+ES on winter, (b) SCEM-PV and (c) SCEM-PV+ES on summer month.

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average REM exported energy by 27-1= 26 kWhr in the *SCEM-PV+ES* (e) scenario compared with the *HEMS-PV+ES* (c) scenario. The P2P transaction is also boosted by the presence of ES (*SCEM-PV+ES* scenario) driven by energy arbitrage in the winter month and surplus PV generation in the summer month, as evident in the *SCEM-PV+ES* scenarios (e) (marked with orange) while comparing with SCEM scenario without ES, *SCEM-PV* (d).

E. Network impact

As described in Section V-B, the inclusion of DER assets, especially ES influenced by the SCEM has significantly altered the smart homes' daily profile. The LVDN hosting the smart homes is usually designed to be in a “fit-and-forget” approach and is not generally equipped with monitoring and control devices. Therefore, it is imperative to understand how the change of profiles due to the integration of DERs impacts the LVDN and the homes connected to it consecutively. This study only presents the voltage profile at nodes connecting smart homes as it directly affects the network stability. Fig. 9 depicts the voltage profile of 10 consecutive days at LVDN nodes for scenarios- SCEM-PV+ES in winter and SCEM-PV in summer months. SCEM-PV+ES scenario on winter month has certain nodes experiencing under-voltage situations due to the high charging of ES. On the other hand, SCEM-PV shows overvoltage conditions at nodes resulting from high surplus PV injection. However, incorporating ES has eliminated the overvoltage problem, shown in the SCEM-PV+ES scenario.

F. Recommendations

Results from this study premises for several recommendations that are crucial for harnessing the benefits brought forward by SCEM in the transition of residential customers.

The study has found that the SCEM operation is intertwined with the grid tariff design, as an exogenous price signal to the SCEM, especially in the presence of ES. Grid tariff is determined by the regulatory authority and is required to adhere few design principles, e.g. cost-reflectivity, non-distortionary, cost recovery, non-discriminatory etc [49]. Therefore, regulatory authority requires to carefully design the future grid tariff that fosters the SCEM and hence, energy activism of customers in the community.

The P2P transaction in SCEM only boosts when the pricing of P2P energy exchange is capped by the ToU and feed-in tariffs, as assumed in the paper. Hence, in designing future grid tariffs, the locational dimension of grid tariff may appear relevant considering the localised, P2P energy exchange nature of the SCEM.

Energy arbitrage among customers in the energy community is dominant in the P2P transaction during winter, in the presence of residential ES and static ToU tariff. This endangers the retailer's revenue under the existing business model as a number of households are buying stored energy (stored from retailer-supplied energy at low tariff hours) from their peers through energy arbitrage rather than buying directly from the retailer. This opens up the necessity of investigating adaptation of a localised, community-based market (e.g. SCEM) to the retail electricity market and the need for changes in the retailer's business model.

The network performance study shows SCEM has resulted in poor voltage performance. Though the analysis has been performed for the extreme case where the entire community under the same substation participates in the SCEM with the same DER portfolio, the detailed network hosting capacity of the SCEM can provide insights into the penetration level of SCEM under a single substation for secured network operation.

Till now, the R&D projects on SCEM are taking place in the regulatory sandbox due to the absence of clear direction on SCEM in regulation. The above-mentioned concerns derived from the results are relevant to be addressed for the development of existing and/or emerging regulations, grid codes, standards, legal framework, business model and central electricity market arrangement, which facilitates real-life roll-out of energy community-centred local market.

VI. CONCLUSIONS

The transition of energy-passive homes to energy-active ones through incorporating DERs and demand response capabilities can further be augmented with the introduction of SCEM. The research contributes to the discussion of the transitional stages of residential households by investigating from a short-term operational perspective different types of smart homes categorised based on DER assets, flexibilities and participation in SCEM. The result shows that the smart homes with PV and ES under SCEM achieve the highest benefits in extreme conditions for both typical summer and winter. The presence of ES facilities in homes’ premises plays a crucial role as the ability to store allows the smart homes to maximise the consumption of locally generated, green energy and energy arbitrage.

Results also demonstrate that the differential tariff scheme (static ToU tariff) contributes significantly to the operation of smart homes with ES on winter days. Conversely, the driving factor on summer days involves primarily maximal consumption of locally generated electricity. The provision of P2P transactions under the SCEM opens the opportunity of energy arbitrage for smart homes with ES and further boosts the local consumption of locally generated electricity (compared to the HEMS scenario). However, this leads to another issue, heightening of high demand peak further in wintertime resulting in an under-voltage situation in the network. The findings in the study identify, quantify and synergise the underlying factors constituting the gradual shift of residential households under various scenarios across different seasons while exploring from a short-term operational horizon.

Envisaged future work includes the following extensions. Impact of variety of dynamic tariff schemes on smart homes under SCEM. Inclusion of uncertainty associated with generation and consumption. Cyclic degradation of ES is crucial to be acknowledged to quantify the benefits of ES under SCEM properly. Future research will also extend on the study of SCEM operation under different penetration of households and DER capacity. Detailed analysis of network performance, substation congestion, and network unbalance study, after inclusion of certain network constraints in the HEMS/SCEM model, will be carried out to understand the hosting capacity of SCEM in the residential network.

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