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RESEARCH ARTICLE

Impacts of Community Energy Trading on Low Voltage Distribution Networks

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ABSTRACT The wide spread of distributed energy resources (DERs) enabled the transformation of the passive consumer to an active prosumer. One of the promising approaches for optimal management of DERs and maximizing benefits for the community and prosumers is community energy trading (CET). CET gives the prosumers the flexibility and freedom to trade electricity within the neighborhood and maximize their economic benefits besides maximizing local consumption of renewable energy sources generation. Despite the economic benefits of CET for individuals and the whole community, it could cause impacts on the low voltage distribution network (LVDN). Therefore, there is a need for a comprehensive evaluation of the potential impacts of CET on LVDN. This study compared CET with the home energy management system (HEMS) regarding community operation costs and interaction with the retailer. Furthermore, this paper focused on assessing the impacts of CET between prosumers on the phase unbalance of LVDN. Moreover, the impacts on transformer loading, lines loading, and voltage deviations are assessed. Compared to the corresponding HEMS scenarios, the results demonstrate that CET reduces the community electricity cost by up to 31%. CET resulted in better self-consumption by reducing the exports to the retailer by 93% and better self-sufficiency by covering up to 54% of energy demand by community DERs. However, CET resulted in increasing the community peak demand, accordingly, higher impacts on the LVDN. The transformer is lightly loaded in all scenarios. CET resulted in limit violations in some lines, whereas most are lightly loaded. The voltage magnitude and voltage unbalance exceeded the acceptable limits at some nodes of the LVDN.

INDEX TERMS Local electricity market, energy community trading, energy community, transactive energy, distributed energy resources, electric vehicle, energy storage.

I. INTRODUCTION

In many countries, distributed energy resources (DERs) are being integrated with high penetration at the distribution networks. These DERs are expected to cause many violations at the distribution networks (DNs) if not effectively managed. Therefore, many approaches were proposed for integrating DERs in future power systems and maximizing DER owners' benefits, such as home energy management system (HEMS) [1]. However, in this approach, there is no coordination between DERs, and the grid constraints are not considered. As a result, the grid limits violation could occur. Therefore, HEMS with operating envelopes specified by the distribution system operator (DSO) is proposed to consider the grid constraints [1]. In the HEMS approach, DERs owners feed their extra energy to retailers and receive feed-in tariff (FIT) price, which is usually supported to incentivize more DERs installation. However, this support is reduced or eliminated in many countries [2], which could reduce the economic benefits of DERs installations.

Moreover, DERs could be integrated into a microgrid connected to the grid or operating in an isolated mode. Furthermore, DERs dispersed in large geographical areas could be aggregated to act as a single power plant called a

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virtual power plant (VPP). VPP could participate in wholesale energy markets and provide different ancillary services for transmission system operator (TSO) or DSOs [3], [4]. Another promising approach for integrating DERs into future power systems is community energy trading (CET). Similar approaches are also known in the literature as peer-to-peer (P2P) energy trading, transactive energy, community self-consumption, or local electricity markets (LEMs). Considering the early stage of research on this topic, there is still confusion between these terms, and they are usually used interchangeably. Recent studies tried to identify the unique characteristics of each of them [5]. Since this study optimizes the operation cost of a community while considering local energy trading within the community, CET is selected as the most accurate term for our centralized local energy trading. CET enables prosumers to sell their extra energy production to neighbors with an energy deficit. The CET could increase competition between retailers and small local DERs [6], achieve a supply-demand balance in the local community, increase self-consumption of local generation from renewable energy sources (RESs), reduce imports from the main grid, and maximize the economic benefits of prosumers/consumers by receiving better prices in CET than the retailer prices [7]. This could result in a faster pace of DERs deployment in residential communities.

Many academic studies investigated local energy trading. For instance, a P2P energy trading in a residential community in London, UK, was proposed in [8]. The community contains various DERs, such as photovoltaic (PV) generation, wind generation, and batteries (i.e., energy storage system (ESS)). The results showed the effectiveness of the local P2P trade between community houses in reducing the consumption from the main grid, increasing community self-sufficiency, and reducing the total electricity costs of the community. Another study proposed P2P energy trading in a community of industrial buildings in a Norwegian industrial site [9]. P2P energy trading resulted in a reduction of electricity cost, and maximization of local generation consumption. The authors of [10] proposed an auction-based P2P energy trading between residential buildings in Spain, considering a different number of buildings participating in the local energy trading. These studies considered the presence of a central entity that manages the local trade between peers. Centrally-managed P2P energy trading ensures social welfare maximization. However, it has some limitations, such as a single point of failure, prosumers' privacy concerns, etc. [11]. To overcome these limitations, many studies proposed using distributed ledger technologies to manage P2P energy trading in a decentralized way where no central entity is required to operate the market [11], [12]. Ref. [13] proposed a blockchain-based iterative double auction for P2P energy trading between EVs in a community. This LEM enables EVs with surplus energy in their batteries to trade it with other nearby EVs that need energy and gain financial benefit. The results showed that the proposed blockchain-based P2P energy trading enabled social welfare maximization while protecting EVs privacy and improving transactions security.

Besides academic studies, P2P energy trading received considerable interest from start-ups and pilot projects. LO3 company was the first to implement a blockchain-based P2P energy trading in a community in New York, USA, where the neighbors can trade electricity with each other [14], [15]. In another pilot project called Quertierstrom, a blockchain-based P2P energy trading in an energy community in Switzerland was implemented [16]. The market participants submit their bids, and the market is cleared every 15 minutes based on a double auction. Powerledger start-up developed a blockchain-based platform that enables P2P energy trading between community neighbors [17]. They participated in many projects for P2P energy trading in many countries such as Australia, Japan, USA, among others [18].

Most of the P2P energy trading studies and pilot projects focused on the market design (i.e., bidding strategy, market clearing approach, centralized or decentralized architecture, etc.), scalability of the market, the connected DERs in the studied power system, and technologies that enable implementation of these markets such as blockchain, and little attention was given to the impact of P2P energy trading on physical grid constraints [19]. Recent studies proposed many methods to consider the grid in the market model. There are studies that used sensitivity coefficients such as voltage sensitivity coefficients, loss sensitivity factors, or power transfer distribution factors [20]. Other studies used DC power flow equations [21], [22], or AC power flow equations [23] for grid representation. Only energy transactions that do not violate grid limits are allowed when the grid is considered in the market model. However, each of these approaches has some limitations [24]. For instance, the coefficients approximate the physical grid. DC power flow is more suitable for the transmission level and inaccurate at the distribution level [25]. AC power flow needs a high computational power because of the non-linear power flow equations, and the optimum solution is not guaranteed because of the non-convexity of the optimization problem.

These studies did not focus on assessing the impacts of local energy trading on the physical grid but on providing different approaches to integrate the physical grid constraints in the market model and avoid any constraints violations. Moreover, signals of dynamic prices, network tariffs, and power losses were also proposed by previous studies to represent the network constraints [19]. Furthermore, a few studies run a power flow to evaluate the impact of local energy trading on the distribution network as a second step after clearing the market [24], [26].

The impacts of high DERs integration in low voltage distribution networks (LVDNs) received significant attention from many studies [27], [28]. They studied the impacts of EVs, PVs, etc., on peak demand, transformer loading, lines loading, voltage deviation, and power losses [29], [30], [31].

The impacts of single-phase DERs on phase unbalance at LVDNs were studied by many studies. The impacts of EVs charging on LVDN phase unbalance were assessed in [32]. The results found that the voltage unbalance limit is exceeded at the 50 % EV penetration level. To mitigate EVs impacts on the power system, many smart charging strategies were developed [27]. The impacts of single-phase PV generation on phase unbalance of LVDNs in two countries were assessed in [33]. The results found that PV generation caused a violation of voltage unbalance limits for a few studied scenarios.

Considering that the grid constraints are not considered in the local energy trading model in most of the proposed market designs. Few studies assessed the impacts of local energy trading between residential consumers on LVDN limits considering different DERs, market designs, and operational conditions. For instance, the impact of CET on voltage deviation on LVDN was assessed in [7]. The study found that voltage exceeded the lower limits for some nodes in winter for CET (PV+ESS) scenario. In addition, the voltage exceeded the upper limits (i.e., overvoltage) for some nodes in summer for CET (PV) scenario due to high PV generation. This voltage rise is caused by the excess PV generation and is not due to anything related to CET. This overvoltage problem was eliminated when ESS was connected. Another study assessed the impact of CET on voltage deviation and losses on LVDN [24]. The results showed that CET induced higher under voltages and energy losses in winter with the presence of PV and ESS compared to other scenarios.

The impact of P2P energy trading on power losses and voltage in large-scale LVDN was studied in [26]. P2P trade caused a negligible increase in losses for the whole day (less than 0.5%) compared to the scenario with no P2P energy trading. Moreover, the voltage was within acceptable limits during hours with high P2P trade. This study considered a limited P2P trade since only 25% of consumers have PV (i.e., prosumers), and less than 50% of the prosumers have ESS or controllable loads. The impacts of CET on peak demand, losses, and voltage levels of LVDN in Norway were evaluated in [34]. The LVDN has 52 prosumers with PV, ESS, and EVs connected. The study concluded that CET resulted in higher energy losses and voltage fluctuations compared to the scenario with HEMS. Moreover, CET increased peak demand and voltage fluctuations compared to the reference scenario (i.e., no CET and no DERs). However, this study did not consider the connection of ESS and EVs simultaneously at the LVDN. Ref [35] assessed the impact of CET on LVDN voltage considering the presence of PV, WG, ESS, and EVs. The study found that the voltage was within acceptable limits.

At the LVDN, the DERs are connected to a single phase; however, for simplicity, most of the local energy trading studies assume the DERs are connected as a three-phase, so the phase unbalance was neglected. Based on that, assessing the impacts of local energy interactions between energy community prosumers on phase unbalance is important. Limited attention was given to the unbalanced nature of DERs in local energy trading in previous studies [19], and they studied a limited number of possible operation scenarios in the LVDN. For instance, ref. [6] studied the impact of P2P energy trading on voltage unbalance of LVDN was studied for only one day and considered one operation scenario. The study considered the presence of PV and EVs operating in the charging mode only and did not consider V2G. Moreover, ESS was not considered in this study. The study results showed a negligible variation in voltage unbalance due to the moderate level of P2P trade compared to the reference scenario with no P2P trade. Furthermore, P2P trade shows a negligible effect on energy losses, voltage variation, and peak demand. Table 1 provides an overview of related studies that evaluated the impacts of local energy trading on LVDNs.

The contributions of this paper are the following:

- Model a CET for DERs connected to an unbalanced LV distribution network considering various operation scenarios with generation profiles and real demand measurements from Madrid, Spain.
- A techno-economic comparison of CET-based coordinated DERs management with HEMS, where prosumers manage their DERs individually. The studied approaches are compared in terms of energy exchange with the retailer, locally traded energy, the total operation cost of the community, and the percentage of demand covered by community DERs.
- Consider many DERs such as PV, ESS (i.e., batteries), and EVs.
- Evaluate the impact of CET on the transformer loading, lines loading, voltage deviation, and voltage unbalance of LVDN.

The rest of the paper is organized as follows. The CET model and HEMS model are presented in section II. Section III describes the studied LVDN, load profiles, generation profiles, DERs characteristics, retailer prices, and the studied scenarios. Section IV presents the results of the comparison between the seven studied scenarios and the assessment of the impacts on the LVDN. The conclusion is provided in section V.

II. PROBLEM FORMULATION

The study has two separate cascaded steps. In the first step, a centralized CET optimization is performed, and its output is the energy dispatch of market participants (i.e., homes) for the considered time horizon T (i.e., one month). The market decisions are optimized every 1 hour interval (t). MATLAB is used to develop the market model. In the second step, a power flow is performed to evaluate the impacts on the physical grid based on the market results from the first step. The load flow is performed using Pandapower software [36], [37], which is an open-source tool based on Python for power system studies. A 3-phase AC power flow is performed because the case study is unbalanced LVDN, and the focus of the study is to evaluate the phase unbalance in addition to components loadings and voltage at different nodes of the LVDN. Figure 1

TABLE 1. Comparison of relevant articles that studied the impacts of local energy trading on low voltage distribution networks.

Ref.	Data	DERs	G2V	V2G	Study time	voltage unbalance	Assessed impacts
[6]	England	PV, EV	Yes	No	1 day	Yes	Voltage, losses, peak demand
[7]	Ireland	PV, ESS	No	No	January, June	No	Voltage
[24]	Ireland	PV, ESS	No	No	January, June	No	Voltage, Losses
[26]	Australia	PV, ESS, controllable loads	No	No	1 day	No	Voltage, Losses
[34]	Norway	PV, ESS/EV	Yes	No	21 days (summer)	No	Voltage, losses, peak demand,
[35]	England	PV, WG, ESS, EV	Yes	Yes	1 month	No	Voltage
This paper	Spain	PV, ESS, EV	Yes	Yes	1 month July	Yes	Peak demand, components loading, voltage

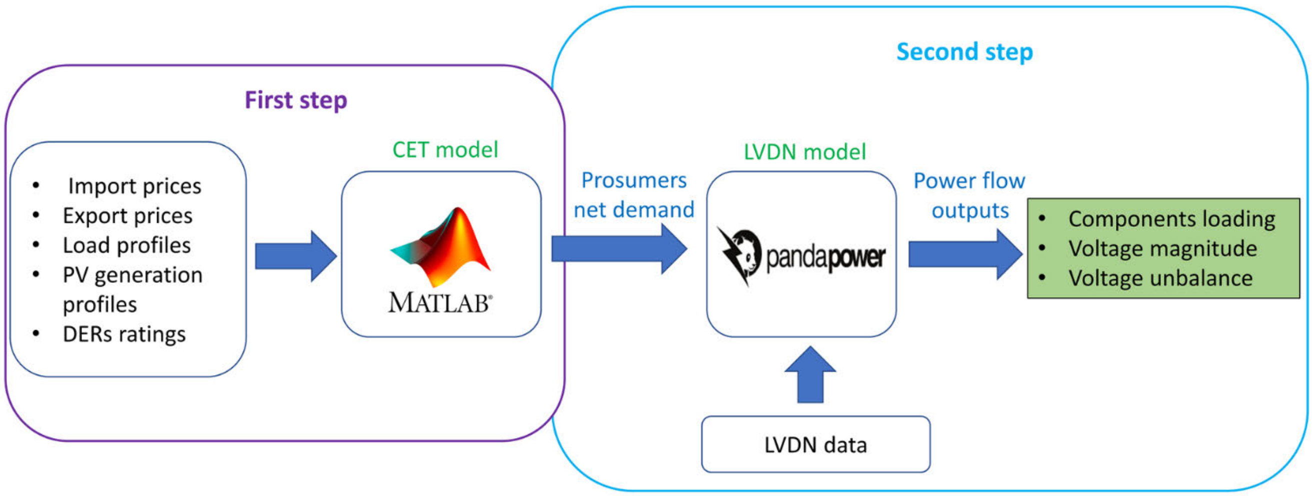

FIGURE 1. Schematic diagram of community energy trading impacts evaluation.

shows a schematic diagram illustrating the sequence of the CET impacts evaluation. The market model in MATLAB (first step) receives load profiles, PV generation profiles, import prices, export prices, and DERs characteristics as inputs. The output of the market is the prosumers' DERs dispatch and net demand profile needed for power flow. The market outcomes and the LVDN data are the inputs to Pandapower (second step) to perform 3 phase power flow every 1 hour. The output of Pandapower is the voltage unbalance value at the homes nodes, components loadings, and voltage magnitude at different phases.

A. COMMUNITY ENERGY TRADING MARKET MODEL

The CET is modeled as a linear multi-period optimization problem for a trading period T and considering h homes. A similar model for centralized CET has been proposed in recent studies [7], [8], [34]. The objective of the CET is to minimize the cost of community energy imports from the retailer and maximize the profit of exporting the community energy surplus to the retailer. This is achieved by incentivizing local energy trading between peers within the community and the flexibility of ESS and EVs. The community objective function is given in (1), and it is subjected to power balance constraints, DERs operation limits constraints, and constraints of P2P trading within the community. In this study, it is assumed that for CET scenarios, the sum of home earnings from selling energy is equal to the sum of home purchase payments for the locally traded energy. Therefore, they are not included in the objective function. $p_G^{(t)}$ is the import (i.e., buying from retailer) price and $p_F^{(t)}$ is the export

TABLE 2. Variables, scalars, parameters, and sets of the community energy trading model.

Variables	
$G^{(t,h)}$	Energy consumption from the grid of home h at instant t
$I^{(t,h)}$	Imports from peers in the community to home h at instant t
$E^{(t,h)}$	Energy stored at ESS of home h at instant t
$D^{(t,h)}$	ESS discharge power at home h at instant t
$D_{EV}^{(t,h)}$	EV discharge power at home h at instant t
$X^{(t,h)}$	Exports to peers in the community from home h at instant t
$E_{EV}^{(t,h)}$	Energy stored at EV of home h at instant t
$F^{(t,h)}$	Energy supply to the main grid from home h at instant t
$C^{(t,h)}$	ESS charge power at home h at instant t
$C_{EV}^{(t,h)}$	EV charge power at home h at instant t
$I_p^{(t,h\leftarrow p)}$	Energy imported to home h from its peer p at instant t
$X_p^{(t,h\rightarrow p)}$	Energy exported from home h to its peer p at instant t
Parameters, scalars, and sets	
$\text{dem}^{(t,h)}$	Demand of home h at instant t
$\text{pv}^{(t,h)}$	PV generation of home h at instant t
$p_G^{(t)}$	Import price at instant t
$p_F^{(t)}$	Export price at instant t
η^c	ESS charging efficiency
η^d	ESS discharging efficiency
$P_d^{(t,h)}$	Net power demand of home h at instant t
η_{EV}^c	EV charging efficiency
η_{EV}^d	EV discharging efficiency
$\bar{C}$ and $\bar{D}$	Upper limits of charging and discharging powers of ESS
$\bar{C}_{EV}$ and $\bar{D}_{EV}$	Upper limits of charging and discharging powers of EV
$\bar{E}$ and $\underline{E}$	Upper and lower limits of ESS storage level
$\bar{E}_{EV}$ and $\underline{E}_{EV}$	Upper and lower limits of EV storage level
$b^{(t)}$	Binary parameter to define if the EV is connected to the LVDN
Δt	Trading period duration
ψ^{P2P}	P2P trade loss factor
$t \in T$	Time instant t in time horizon T
$h, p \in H$	Home h and peers p in a community of H homes

(i.e., selling to retailer) price at time instant t. $G^{(t,h)}$ is the energy consumption from the main grid (i.e., bought energy from retailer) at time instant t for home h. $F^{(t,h)}$ is the energy supply to the main grid (i.e., sold energy to retailer) at time instant t from home h. Linear programming is used to solve the optimization problem. The definition of variables, parameters, scalars, and sets are given in Table 2. The variables are represented in upper case letters, whereas parameters and scalars are in lower case to distinguish them easily in the mathematical model equations.

$$min \sum\nolimits_t \sum\nolimits_h (p_G^{(t)} \cdot G^{(t,h)} - p_F^{(t)} \cdot F^{(t,h)})\Delta t \tag{1}$$

At each home node, there should be a balance between supply and demand at each time instant t as given in (2). It means that the sum of consumption from the grid $G^{(t,h)}$, imports from peers in the community $I^{(t,h)}$, PV generation $\text{pv}^{(t,h)}$, ESS discharge $D^{(t,h)}$, and EV discharge $D_{EV}^{(t,h)}$, must be greater or equal to the sum of exports to peers in the community $X^{(t,h)}$, demand $\text{dem}^{(t,h)}$, supply to the main grid $F^{(t,h)}$, ESS charge $C^{(t,h)}$, and EV charge $C_{EV}^{(t,h)}$. This equation represents a home that has PV, ESS, and EVs. The power balance equation will be different for other homes that have other DERs or no DERs installations by eliminating some terms from (2).

$$\begin{aligned} G^{(t,h)} + I^{(t,h)} + \text{pv}^{(t,h)} + D^{(t,h)} + D_{EV}^{(t,h)} \\ \geq X^{(t,h)} + \text{dem}^{(t,h)} + F^{(t,h)} + C^{(t,h)} + C_{EV}^{(t,h)} \\ \forall t \in T, \quad \forall h \in H \end{aligned} \tag{2}$$

The installed ESS should operate within its ratings. The charging $C^{(t,h)}$ and discharging $D^{(t,h)}$ are limited by the power rating of the power electronic converter that connects the ESS to the LVDN. The lower limits of charging and discharging powers are zero. The upper limits of charging and discharging powers are $\bar{C}$ and $\bar{D}$ respectively, as given in (3) and (4). Moreover, the ESS has lower and upper limits of energy stored $E^{(t,h)}$ in kWh as given (5). The ESS state of charge (SoC) is assumed to remain between 20% and 100%.

$$0 \leqslant C^{(t,h)} \leqslant \bar{C} \quad \forall t \in T, \ \forall h \in H \tag{3}$$

$$0 \leqslant D^{(t,h)} \leqslant \bar{D} \quad \forall t \in T, \ \forall h \in H \tag{4}$$

$$\underline{E} \leqslant E^{(t,h)} \leqslant \bar{E} \quad \forall t \in T, \ \forall h \in H \tag{5}$$

The energy stored at each ESS $E^{(t,h)}$ in a time instant t for a home h is calculated by (6). Where, η^c and η^d are the charging and discharging efficiency, respectively. $E^{(t-1,h)}$ is the energy stored at time instant $t-1$. The initial value of the SoC of each ESS on day 1 is a random value higher than or equal to 20% (i.e., 2.7 kWh). For day 2 the ESS storage level at the first hour is the last value of the day 1 ESS storage level. The same concept applies to any other day of the considered simulation period.

$$E^{(t,h)} = E^{(t-1,h)} + \eta^c \cdot C^{(t,h)}\Delta t - (1/\eta^d) \cdot D^{(t,h)}\Delta t \quad \forall t \in T, \quad \forall h \in H \tag{6}$$

Similarly, the installed EVs should operate within their ratings. The charging $C_{EV}^{(t,h)}$ and discharging $D_{EV}^{(t,h)}$ are limited by the power rating of the charger that connects the EV to the LVDN. The lower limits of charging and discharging powers are zero. The upper limits of charging and discharging are $\bar{C}_{EV}$ and $\bar{D}_{EV}$ respectively, as given in (7) and (8). Moreover, the EV has lower and upper limits of energy stored $E_{EV}^{(t,h)}$ in kWh as given (9) [9].

$$0 \leqslant C_{EV}^{(t,h)} \leqslant \bar{C}_{EV} \cdot b^{(t)} \quad \forall t \in T, \ \forall h \in H \tag{7}$$

$$0 \leqslant D_{EV}^{(t,h)} \leqslant \bar{D}_{EV} \cdot b^{(t)} \quad \forall t \in T, \ \forall h \in H \tag{8}$$

$$\underline{E}_{EV} \leqslant E_{EV}^{(t,h)} \leqslant \bar{E}_{EV} \quad \forall t \in T, \ \forall h \in H \tag{9}$$

$b^{(t)}$ is a binary parameter to define if the EV is connected to the LVDN for charging at the time instant t as given in (10). The value of $b^{(t)}$ is 1 when EV is connected to the LVDN and is 0 when EV is not connected to the LVDN.

$$b^{(t)} = \begin{cases} 1, & \textit{if EV is connected to the LVDN at} \\ & \quad \textit{time instant } t \\ 0, & \textit{othewise} \end{cases} \tag{10}$$

The energy stored at each EV $E_{EV}^{(t,h)}$ that is connected to the grid in a time instant t is calculated by (11). Where η_{EV}^c and η_{EV}^d are the EV charging and discharging efficiency, respectively. $E_{EV}^{(t-1,h)}$ is the energy stored at time instant $t-1$. The initial value of energy stored in each EV on day 1 is a random value higher than or equal to 4.8 kWh (i.e., 20% SoC). For day 2 the EV storage level at the first hour of the day is the last value of day 1 EV storage level. The same concept applies to any other day of the considered simulation period. The EVs are assumed to be connected to the grid from 5 pm to 8 am every day and used for transportation during the other hours of the day. The EV battery SoC decreases when it is used for transportation, and the initial value of SoC when the EV starts charging depends on the SoC when it is disconnected from the grid and driving distance. The EV battery SoC is assumed to remain between 20% and 100%. The EV battery SoC value at departure time (i.e., 8 am) should not be less than 75% to guarantee satisfying EV owner mobility needs and comfort.

$$E_{EV}^{(t,h)} = E_{EV}^{(t-1,h)} + \eta_{EV}^c \cdot C_{EV}^{(t,h)}\Delta t - \left(1/\eta_{EV}^d\right) \cdot D_{EV}^{(t,h)}\Delta t \quad \forall t \in T, \quad \forall h \in H \tag{11}$$

In the local community, the import of prosumer h from peer p is equal to the export of p to h at each time instant t considering the P2P trade losses at LVDN as given in (12). ψ^{P2P} represents the losses in LVDN due to P2P trade. 5% losses are assumed in P2P trade within the community (i.e., $\psi^{P2P} = 0.95$).

$$I_p^{(t,h\leftarrow p)} = \psi^{P2P} \cdot X_p^{(t,p\rightarrow h)} \quad \forall p \neq h \tag{12}$$

Each home with DERs installed can sell energy to any peer in the community. The total sold (i.e., exported) energy $X^{(t,h)}$ from any home $h \in H$ at time instant t is the sum of energy exported $X_p^{(t,h\rightarrow p)}$ from this home h to another peer $p \in H$ as given in (13).

$$X^{(t,h)} = \sum\nolimits_{p\neq h} X_p^{(t,h\rightarrow p)} \quad \forall t \in T, \ \forall h \in H \tag{13}$$

Similarly, the total purchased (i.e., imported) energy $I^{(t,h)}$ for any home $h \in H$ at time instant t is the sum of energy imported $I_p^{(t,h\leftarrow p)}$ for this home h from another peer $p \in H$ as given in (14).

$$I^{(t,h)} = \sum\nolimits_{p\neq h} I_p^{(t,h\leftarrow p)} \quad \forall t \in T, \ \forall h \in H \tag{14}$$

As the P2P trading happens within the community, the sum of the homes sales must be equal to the sum of the homes purchases considering the P2P trade losses at LVDN as given in (15)

$$\sum\nolimits_h \psi^{P2P} \cdot X^{(t,h)} = \sum\nolimits_h I^{(t,h)} \quad \forall t \in T \tag{15}$$

The variable CET price is assumed to be bounded between the import price and export price to make it profitable for all market participants (i.e., buyers and sellers) to trade energy within the community. The buyer buys energy from peers at a lower price than the import price, and the seller sells energy to peers at a higher price than the export price. The DERs characteristics are described in section III-B.

For the HEMS scenarios, which have no local energy trading, each home individually dispatches its DERs to minimize the costs of importing electricity from the retailer and maximizing revenues from exporting electricity to the retailer. The objective function of each home for the HEMS scenario is given in (16). The objective function is subjected to power balance constraints (17), and DERs operation limits constraints (3) to (11).

$$min \sum\nolimits_t (p_G^{(t)} \cdot G^{(t)} - p_F^{(t)} \cdot F^{(t)})\Delta t \quad \forall t \in T \tag{16}$$

$$G^{(t)} + \mathrm{pv}^{(t)} + D^{(t)} + D_{EV}^{(t)} \geq \mathrm{dem}^{(t)} + F^{(t)} + C^{(t)} + C_{EV}^{(t)} \quad \forall t \in T \tag{17}$$

B. IMPACTS OF CET ON LVDN

For each scenario, the net power demand $P_d^{(t,h)}$ of each home h at each time instant t is calculated by (18). The ESS and EV charging and discharging are not included in the equation because it assumed to occur behind the node connection

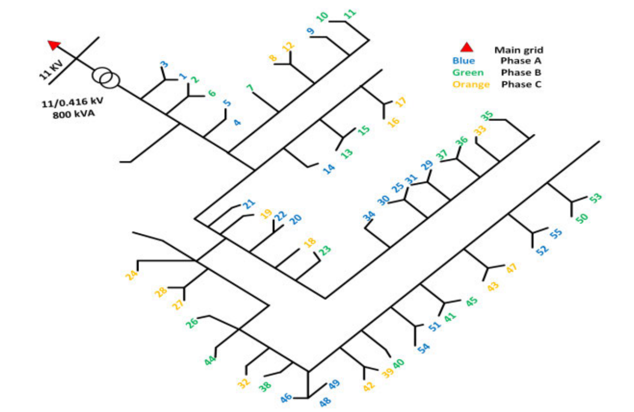

FIGURE 2. Schematic diagram of studied IEEE European low voltage distribution network.

point. Pandapower software receives $P_d^{(t,h)}$ as an input to run the power flow.

$$P_d^{(t,h)} = G^{(t,h)} + I^{(t,h)} - \mathrm{F}^{(t,h)} - X^{(t,h)} \tag{18}$$

In ideal operation scenarios, the load connected to the three phases is even. Under such conditions, no current flows in the neutral line, and the power losses are reduced. However, in reality, there is always unbalance between the load connected to each phase at the DNs. This unbalance should be kept within specific limits to guarantee the normal operation of DNs and the 3-phase loads that require a balanced 3-phase supply. It was easy to maintain the phase unbalance level with limits by distributing the loads evenly at each phase since the consumers in a geographical area have relatively similar consumption habits. This situation is expected to change significantly with the installation of various single-phase DERs (i.e., PV, ESS, EV, etc.). Therefore, many studies were performed to assess the impacts of single-phase DERs on DNs phase unbalance. Local energy trading could change the consumption and production habits of DER owners based on the retailer prices and local trade prices. Therefore, it is crucial to assess the impacts of CET on phase unbalance. The voltage unbalance factor $VUF\%$ has many definitions, and in this study, it is calculated by (19). Based on (19) $VUF\%$ can be defined as a ratio between the negative sequence component and the positive sequence component [38]. The maximum allowed limit of $VUF\%$ is 2 %.

$$VUF\% = \frac{V_2}{V_1} * 100 \tag{19}$$

III. LOW VOLTAGE DISTRIBUTION NETWORK AND DERs CHARACTERISTICS

This section describes the LVDN used as a case study. Additionally, the loads and DERs characteristics are presented. Moreover, the buying/selling price from/to the retailer in Madrid, Spain, is discussed.

A. LOW VOLTAGE DISTRIBUTION NETWORK

Figure 2 shows the single-line diagram of the studied unbalanced LVDN. It is an IEEE European test system that is widely used in DERs integration studies [39]. It has a radial topology which is very common in LVDN in Europe. The test grid is connected to the main grid through MV/LV transformer with 800 kVA rating that steps down the voltage from 11 kV to 416 V with delta/grounded star grounded winding connections. The windings resistance and reactance are 0.4% and 4%, respectively. 55 single-phase residential consumers are connected to the LVDN, and each consumer has a different connection point. The phase of connection of each consumer is differentiated by the consumer number color (i.e., phase A in blue, phase B in green, and phase C in orange). 21 consumers are connected to phase A, 19 consumers are connected to phase B, and 15 consumers are connected to phase C. The profiles are anonymized real measurements for consumers in Madrid, Spain, provided by i-DE, a Spanish DSO that belongs to Iberdrola Group. Each consumer has a different consumption profile, and their profiles were assigned randomly from the recorded measurements of Madrid consumers. In this study, the load profiles are sampled with a 1-hour resolution. The aggregated demand of the 55 consumers for two days is shown in Figure 3. The market model considers only active power trade and does not consider reactive power. Therefore, in the power flow, the loads are assumed to have a constant power factor of 0.95 pu. This paper is relevant in the European context, where policymakers are incentivizing the creation of energy communities that installed DERs and trade energy locally. Different legal and functional entities are being created, such as Citizen Energy Community (Directive 2019/944) or Renewable Energy Community (Directive 2018/2001) [40], [41]. In Spain, the transposition of those entities is still to be done but is expected to be done rather soon.

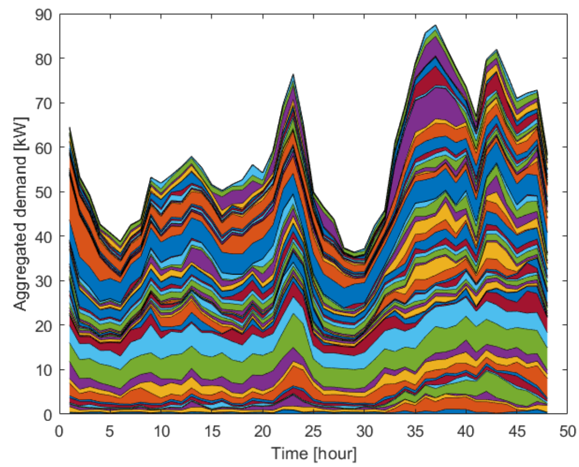

FIGURE 3. Aggregated demand profiles of 55 homes.

B. DERs CHARACTERISTICS AND RETAILER PRICES

Several DERs are connected to the studied LVDN, such as PV, ESS, and EV. Any consumer can have one or a combination of these DERs, and some consumers have no DERs installed. Table 3 shows the DERs installed at each home. The power rating of PV generation is 5 kWp. 33 PV are installed in

TABLE 3. The DERs installed at each home in the community.

home	PV	ESS	EV	home	PV	ESS	EV	home	PV	ESS	EV	home	PV	ESS	EV
1	✓	✓	-	15	✓	✓	-	29	-	-	-	43	✓	-	-
2	✓	✓	✓	16	✓	-	✓	30	✓	✓	-	44	-	-	-
3	✓	✓	-	17	-	-	-	31	-	-	✓	45	✓	✓	-
4	-	-	-	18	✓	✓	-	32	✓	-	-	46	-	-	✓
5	✓	✓	-	19	-	-	-	33	✓	✓	-	47	-	-	-
6	-	-	-	20	✓	✓	✓	34	✓	-	-	48	✓	✓	-
7	✓	-	✓	21	-	-	-	35	-	-	✓	49	✓	-	✓
8	✓	-	-	22	-	-	-	36	-	-	-	50	✓	✓	✓
9	✓	✓	✓	23	✓	✓	-	37	✓	✓	-	51	-	-	-
10	-	-	-	24	✓	-	-	38	-	-	-	52	✓	✓	-
11	-	-	-	25	✓	-	✓	39	✓	-	✓	53	✓	✓	✓
12	✓	✓	✓	26	-	-	-	40	✓	✓	-	54	✓	✓	✓
13	-	-	-	27	✓	✓	-	41	✓	-	✓	55	✓	✓	✓
14	-	-	-	28	-	-	✓	42	-	-	-				

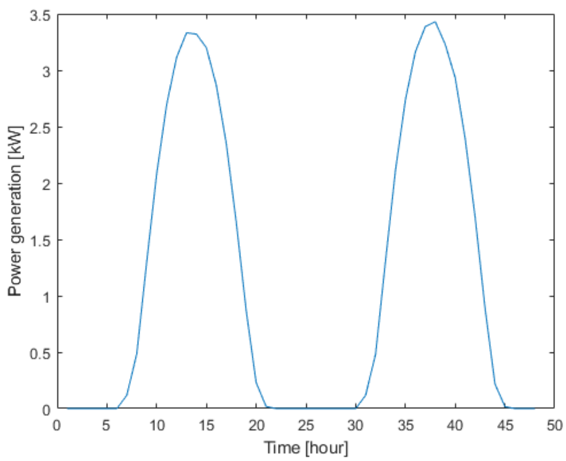

FIGURE 4. PV generation profile of 1 home.

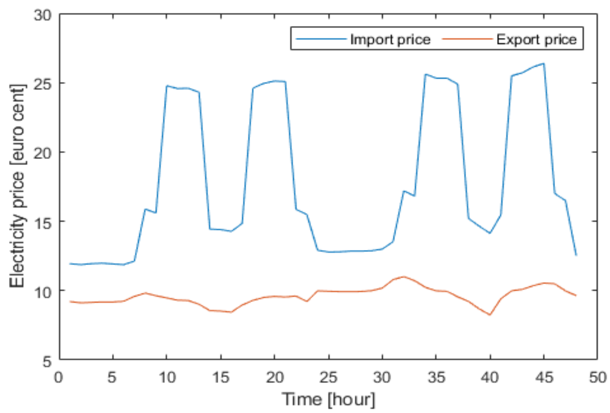

FIGURE 5. Prosumers purchase/sell prices from/to retailer.

the community (i.e., 60% of consumers). The generation profile of one PV for two days is shown in Figure 4. It is obtained from Renewables Ninja for Madrid, Spain [42]. The ratings of ESS are 13.5 kWh/ 5kW, and both the charging and discharging efficiencies are equal to 95%. 22 ESS are installed in the community (i.e., 40% of consumers). The characteristics of EVs are 24 kWh batteries and a 3.6 kW charger rating (i.e., Nissan leaf characteristics). The charging and discharging efficiencies are equal to 96%. The EV chargers are bidirectional and enable absorbing (i.e., G2V) or injecting (i.e., V2G) energy. 18 EV are installed in the community (i.e., 33% of consumers).

In this study, the Spanish prices for buying/selling energy from/to retailers are used. The prosumers buy based on retailer tariff and sell based on self-consumption surplus energy price for the regulated tariff (PVPC) in place in Spain. The prices for July 2021 are obtained from the Spanish TSO Red Eléctrica [43]. Figure 5 shows the retailer prices for the 1st and 2nd of July. The studied scenarios assume possible DERs and penetration levels that could be installed in the future. In this paper, we focused on studying a summer month where a high generation from PV is expected and, consequently, high local energy trading within the community. Moreover, we studied the performance of community energy trading for 1 month in winter (i.e., January), and the results are given in the appendix.

C. STUDIED SCENARIOS

In this study, many operation scenarios are evaluated where different DERs are connected to the grid, and they are dispatched based on CET or HEMS individual optimization without local energy trading. The main features of these scenarios are described in the following points, and they are summarized in Table 4.

- The first scenario is the reference case where no DERs are installed in any home, and the consumers buy their whole electricity demand from retailers at the import price. This scenario is called reference in the rest of the paper.

TABLE 4. Summary of the seven studied scenarios.

#	Scenario	DERs	DERs management	Description
1	Reference	No DERs	No	No DERs are installed in any home, and the consumers buy their whole electricity demand from retailers.
2	PV	PV (60% of consumers)	No	Some homes have a PV installed for self-consumption. The surplus generation is sold to the retailer.
3	CET(PV)	PV (60% of consumers)	CET	Some homes have a PV installed for self-consumption. The surplus generation is sold to the other peers or the retailer.
4	HEMS(PV, ESS)	PV (60% of consumers) ESS (40% of consumers)	HEMS	PV and ESS are installed in some homes. The DERs of each home are optimally managed to reduce the home electricity cost.
5	CET(PV, ESS)	PV (60% of consumers) ESS (40% of consumers)	CET	PV and ESS are installed in some homes, and owners can trade the surplus PV generation or stored energy with peers in the community (i.e., P2P) or sell it to the retailer.
6	HEMS(PV, ESS, EV)	PV (60% of consumers) ESS (40% of consumers) EV (33% of consumers)	HEMS	PV, ESS, and EV are installed in some homes. The DERs of each home are optimally managed to reduce the home electricity cost.
7	CET(PV, ESS, EV)	PV (60% of consumers) ESS (40% of consumers) EV (33% of consumers)	CET	PV, ESS, and EV are installed in some homes, and owners can trade the surplus PV generation or stored energy with peers in the community (i.e., P2P) or sell it to the retailer.

- In the second scenario, some homes have a PV installed. The homes' consumption is covered by their PV generation or from the retailer, and if there is surplus PV generation, they supply it to the retailer and receive the export price. In this scenario, homes with PV cannot trade their surplus generation with neighbors in the community. This scenario is called PV in the rest of the paper.
- In the third scenario, there is a PV installed in some homes. The homes' consumption is covered by their PV generation, peers, or the retailer. The PV owners can trade the surplus generation with peers in the community (i.e., P2P) or sell it to the retailer if there are no peers willing to buy energy at that time instant. This scenario is called CET(PV) in the rest of the paper.
- In the fourth scenario, PV and ESS are installed in some homes. The PV and ESS of each home are optimally managed by HEMS to reduce the home electricity cost, and no local energy trading is allowed. This scenario is called HEMS(PV, ESS) in the rest of the paper.
- In the fifth scenario, PV and ESS are installed in some homes, and owners can trade the surplus PV generation or stored energy with peers in the community (i.e., P2P) or sell it to the retailer if there are no peers willing to buy energy at that time instant. ESS can be charged from the home PV, buying from other peers, or buying from the retailer. This scenario is called CET(PV, ESS) in the rest of the paper.
- In the sixth scenario, PV, ESS, and EV are installed in some homes. The PV, ESS, and EV of each home are optimally managed by HEMS to reduce the home electricity cost, and no local energy trading is allowed. This scenario is called HEMS(PV, ESS, EV) in the rest of the paper.
- In the seventh scenario, PV, ESS, and EV are installed, and owners can trade the surplus PV generation or stored energy in ESS or EV with peers in the community (i.e., P2P) or sell it to the retailer if there are no peers willing to buy energy at that time instant. ESS and EV can be charged from the home PV, buying from other peers, or buying from the retailer. This scenario is called CET(PV, ESS, EV) in the rest of the paper.

IV. RESULTS AND DISCUSSIONS

The results are presented in three parts. The first art presents a comparison between the studied scenarios in terms of energy exchange with the retailer, locally traded energy, the total operation cost of the community, and the percentage of demand covered by community DERs. The second part discusses how different types of homes (i.e., without DERs, with PV, etc.) cover their electricity demand and manage DERs under different scenarios. The third part presents an assessment of the impacts of different scenarios on the transformer loading, lines loading, voltage deviations, and voltage unbalance of LVDN.

TABLE 5. Comparison of the seven studied scenarios for July.

	No DERs	PV		PV+ESS		PV+ESS+EV	
	Reference	PV	CET	HEMS	CET	HEMS	CET
Imports from retailer (kWh)	47228.78	35123.66	24567.22	32810.24	21873.91	38723.78	26620.64
Exports to retailer (kWh)	0	15692.07	4580.02 (-70%)	12820.15	851.91 (-93.35%)	14039.55	927.17 (-93.39%)
Total local energy trading (kWh)	0	0	11112.05	0	15687.87	0	16796.28
Demand by retailer (%)	100	74.37	52.02	69.47	46.31	81.99	56.37
Demand by DERs (%)	0	25.63	47.98	30.53	53.69	18.01	43.63
Peak of grid consumption (kW)	105.91	88.36	88.36	125.92	164.16	159.84	228.96
Total operation Costs (€)	7622.45	4140.09	3324.76	3743.65	2592.33	4165.58	3007.29
CET cost reduction (%)	-	-	-19.69	-	-30.75	-	-27.81
Costs of imports from retailer (€)	7622.45	5543.45	3741.71	4938.34	2672.87	5486.30	3095.71
Revenue of exports to retailer (€)	0	1403.36	416.95	1194.69	80.55	1320.73	88.42

A. COMPARISON OF THE STUDIED SCENARIOS

This section compares the CET scenarios and other scenarios. Table 5 shows a comparison between the seven studied scenarios. For all the studied scenarios, the introduction of CET significantly reduced the amount of energy sold to the retailer by up to 93% and increased community self-consumption by incentivizing local consumption to be covered through exchange between peers in the community. Most of the local generation was traded locally when CET was introduced. Moreover, CET increased community self-sufficiency when ESS and EV are considered, where DERs cover a high percentage of demand. For CET(PV, ESS) scenario, about 54% of demand is covered by DERs, and DERs cover about 44% of demand for CET(PV, ESS, EV).

Figure 6(a) shows the aggregated energy bought from the retailer by community homes for the studied scenarios. It shows that for CET scenarios, there are hours with zero imports from the retailer. In these hours, the prosumers cover their demand with their own DERs or buy from peers at a lower price than the retailer price. Similarly, Figure 6(b) shows that for CET scenarios, usually, a negligible amount of energy is sold to the retailer. The prosumers prefer to sell excess energy to peers at a higher price than the retailer price. This proves that CET can increase the independence of the energy communities from the main grid electricity supply. It can be noticed that PV scenario and CET(PV) have different values for the energy exchanged with the retailer. However, these two scenarios have the same physical flow of energy in the grid. In CET(PV), homes can exchange energy with each other besides exchanging with the retailer. That is why the CET(PV) scenario has lower values of energy exchange with the retailer compared to PV scenario.

The total amount of traded energy in CET scenarios for all homes in the community is given in Figure 6(c) and Table 5. The results show an increase in the amount of traded energy and the trading period between peers in the community when ESS and EV are installed because prosumers can charge ESS or EV when there is high PV generation and sell it at hours with less or no PV generation. For the CET(PV) scenario, there are more hours without local energy trade compared to other CET scenarios. This occurs when the PV generation is low, and it is consumed locally by the PV owner or at night hours when there is no generation for PV.

The results showed that DERs reduce the energy bought from the retailer and the electricity cost for the community. The CET scenarios reduced the community electricity cost compared to all the corresponding scenarios (i.e., with HEMS and the same DERs installed). CET reduced the community electricity cost by about 20% for CET(PV) scenario, 31% for CET(PV, ESS) scenario, and 28% for CET(PV, ESS, EV) scenario.

However, the energy arbitrage of ESS and EVs (i.e., charging at low price hours and discharging at high price hours for home self-consumption or selling to other peers in the community) increased the peak of grid consumption as indicated in Figure 6(a) at hour 25 and Table 5 for the scenarios with ESS installation or EV, and the peak demand is higher in CET scenarios compared to HEMS.

B. OPERATION OF HOMES UNDER DIFFERENT SCENARIOS

The operation of different homes is presented for the studied scenarios to show how the different homes cover their electricity demand and how ESS and EVs behave in different scenarios. Home 10 has no DERs, home 32 has PV generation, home 15 has both PV and ESS, and home 53 has PV, ESS, and EV.

As shown in Figure 7(a), home 10 covered its demand from the retailer in all the scenarios with no CET (i.e., reference, PV, HEMS(PV, ESS), and HEMS(PV, ESS, EV)). When CET is introduced, a portion of the demand is covered by imports from peers because of the lower CET prices compared to the retailer price. For CET(PV) scenario, the imports from peers happen when they have surplus PV generation, and the demand is covered by the grid at night when there is no PV generation, as shown in Figure 7(b). For CET(PV, ESS) scenario, the imports from peers happen at more duration than CET(PV) due to the presence of ESS owned by other peers

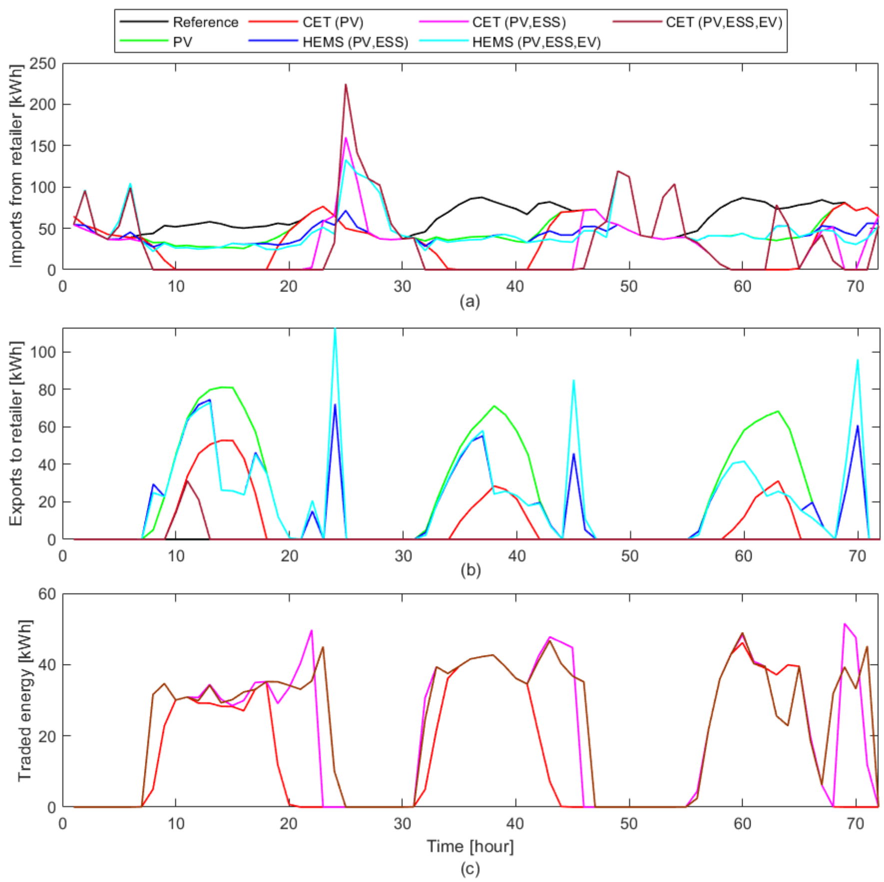

FIGURE 6. Comparison of the studied scenarios in terms of (a) Imported energy from the retailer, (b) Exported energy to the retailer, and (c) Traded energy within the community for CET scenarios.

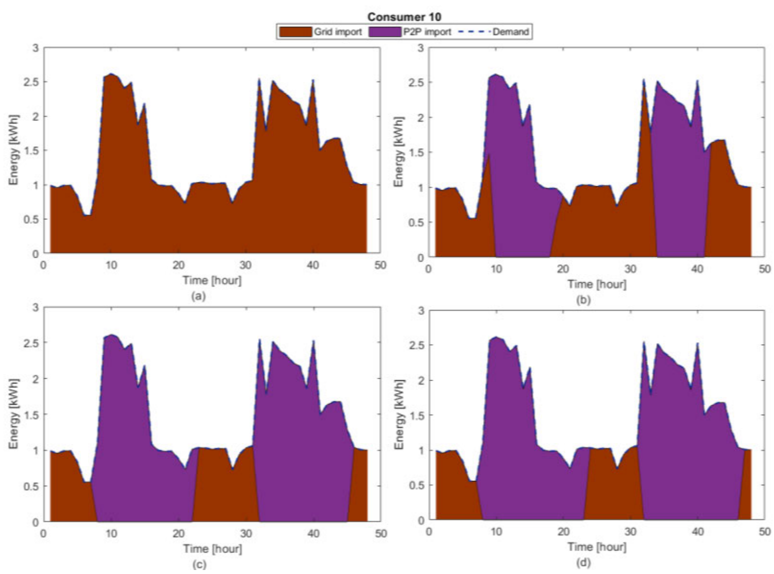

FIGURE 7. Operation of home 10. (a) no CET scenarios, (b) CET(PV) scenario, (c) CET(PV, ESS) scenario, (d) CET(PV, ESS, EV) scenario.

that charges at times with high PV generation or low prices and discharges at times of high prices as shown in Figure 7(c). Similarly, for CET(PV, ESS, EV) scenario depicted in Figure 7(d), the imports from peers happen at more duration than all other scenarios due to the presence of ESS and EV owned by other peers. Although home 10 does not have any

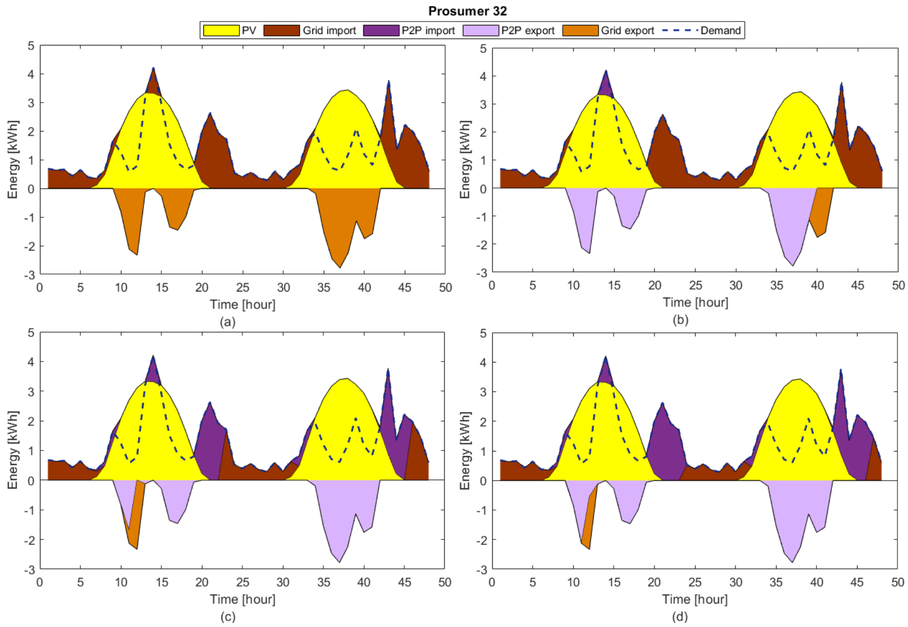

FIGURE 8. Operation of home 32. (a) no CET scenarios, (b) CET(PV) scenario, (c) CET(PV, ESS) scenario, (d) CET(PV, ESS, EV) scenario.

DERs, it is able to actively participate in CET and reduce its electricity bill by buying cheap local electricity imported from the other peers in the community.

For scenarios with no CET, home 32 sells all the excess PV generation to the retailer and buys the needed energy from the retailer when the demand is higher than PV generation and at night hours, as shown in Figure 8(a). For CET(PV) scenario, the local energy trade in the community has a priority over selling to the grid because its price is higher than the price of selling to the retailer. Therefore, home 32 sells excess PV generation to other peers willing to buy energy and sells it to the retailer for time instants when no peers are willing to buy, as shown in Figure 8(b). Moreover, home 32 buys from other peers with excess energy since their price is lower than the retailer price. CET(PV, ESS) scenario showed a different behavior of home 32 due to the ESS owned by other peers that extends the period that home 32 can cover its demand from peers, as shown in Figure 8(c). Similarly, for CET(PV, ESS, EV) scenario, home 32 covered more demand from peers compared to all other scenarios due to the presence of ESS and EV in the community, as shown in Figure 8(d).

For both HEMS (PV, ESS) and HEMS (PV, ESS, EV) scenarios, home 15 covers almost all of its demand by its PV generation during day hours and by ESS discharge at low PV generation and night hours, as shown in Figure 9(a). Home 15 imported a very limited energy from the retailer for the displayed days. The excess PV generation is used to charge ESS or sold to the retailer. Similarly, for both CET(PV, ESS) and CET(PV, ESS, EV) scenarios, home 15 covers almost all of its demand by its PV generation during day hours and by ESS discharge at low PV generation and night hours, as shown in Figure 9(b) and (c). However, in CET scenarios, home 15 prioritizes selling PV generation or ESS discharge to other peers in the community over selling it to the retailer. Therefore, it can be seen that limited energy is sold to the retailer. ESS of the home 15 does energy arbitrage by charging from the grid at low price hours and discharging at higher price hours to cover home demand or sell energy to peers.

For both HEMS (PV, ESS, EV) and CET(PV, ESS, EV) scenarios, home 53 covers a high portion of its demand by its PV generation during day hours and by ESS/EV discharge at low PV generation and night hours as shown in Figure 10. Home 53 prioritizes selling PV generation, ESS discharge, or EV discharge to other peers in the community over selling it to the retailer. For CET(PV, ESS, EV) scenario, ESS and EV of home 53 do energy arbitrage by charging from the grid at lower prices and discharging at higher price hours to cover home demand or sell energy to peers.

C. IMPACTS OF CET ON LVDN

The electrification of transportation and massive adoption of DERs could result in the violation of network constraints. This subsection presents an assessment of the impacts of the studied scenarios on the transformer loading, lines loading, voltage deviations, and voltage unbalance of LVDN. Table 6 shows the maximum transformer loading, maximum line loading, lowest and highest values of voltage at the three phases, and maximum voltage unbalance factor (*VUF%*) recorded during the simulation period (i.e., 1 month) for all studied scenarios. It can be noticed that PV and CET(PV) scenarios have the same impacts on the LVDN since they have the same physical flow of energy, as discussed in subsection IV-A.

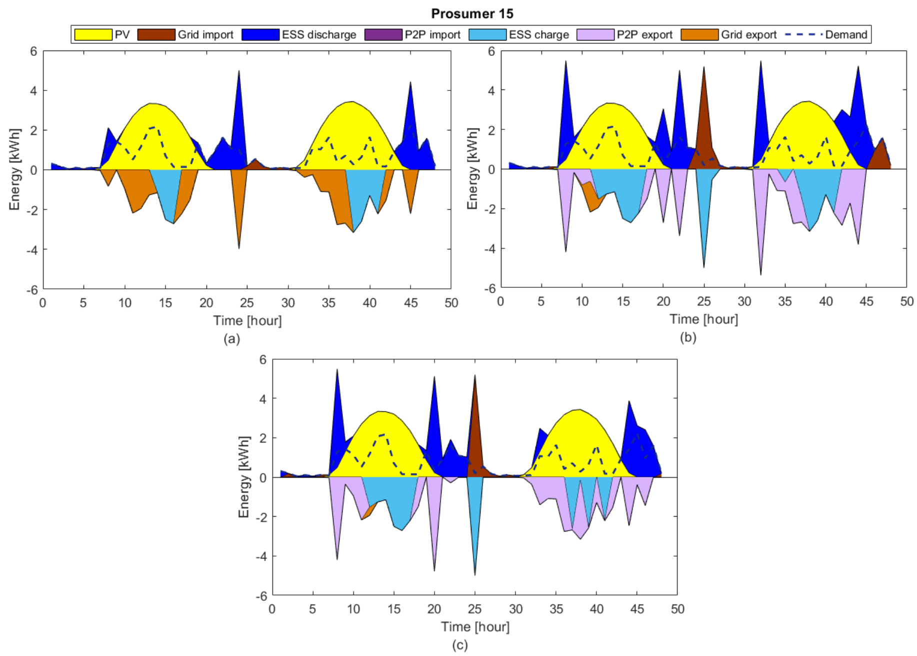

FIGURE 9. Operation of home 15. (a) no CET scenarios (b) CET(PV, ESS) scenario, (c) CET(PV, ESS, EV) scenario.

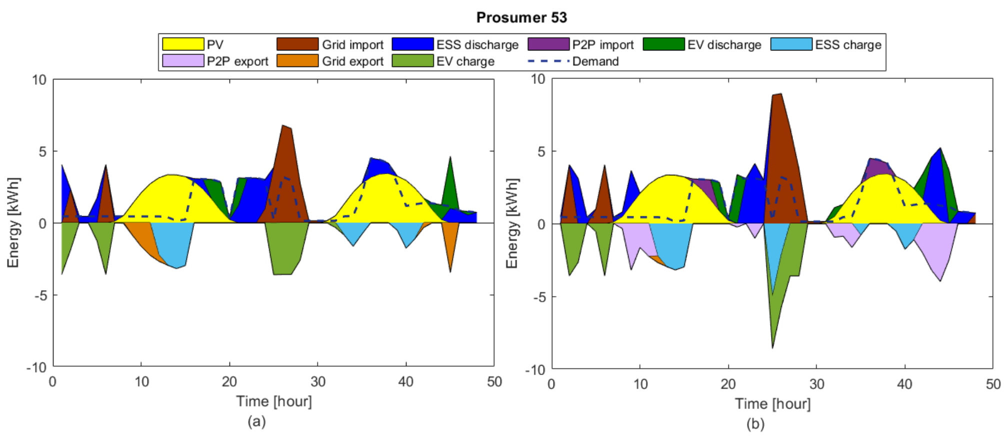

FIGURE 10. Operation of home 53. (a) HEMS (PV, ESS, EV) scenario, (b) CET(PV, ESS, EV) scenario.

1) IMPACTS ON THE TRANSFORMER AND LINES LOADING

In this subsection, the impacts of CET on transformer and lines loading are assessed. Figure 11(a) shows the transformer loading for the seven scenarios in 1 month. For a better visibility, the first 3 days of the month are displayed in Figure 11(b). The transformer loading is low for all scenarios, and the highest loadings are 35.69% and 25.56% for CET(PV, ESS, EV) and CET(PV, ESS) scenarios, respectively. The equivalent HEMS scenarios recorded lower transformer loading than CET scenarios.

Figure 12 (a) shows the loading of the line connected to the transformer LV side for the seven scenarios in 1 month. For a better visibility, the first 3 days of the month are displayed in Figure 12(b). The lines of the studied network have equal current capacity. Therefore, some lines (mainly the lines at the beginning of the LVDN) loading limits are violated for CET(PV, ESS, EV) scenario since all the consumers' energy flows through these lines. This high loading happens when ESSs and EVs charge at the same time when electricity prices are low. Most of the LVDN lines are lightly loaded for all the studied scenarios. The equivalent HEMS scenarios recorded lower line loading than CET scenarios.

2) IMPACTS ON VOLTAGE DEVIATIONS

The LVDNs are subjected to higher voltage deviations compared to the rest of the power system due to their radial topology in most of the cases and lack of voltage control devices. Therefore, the impact of high penetration of DERs on voltage

TABLE 6. Summary of impacts of community energy trading on LVDN.

	No DERs	PV		PV+ESS		PV+ESS+EV	
	Reference	PV	CET	HEMS	CET	HEMS	CET
Maximum transformer loading [%]	14.99	13.65	13.65	17.68	25.56	24.70	35.69
Maximum line loading [%]	46	41.23	41.234	52.80	74.96	73.53	102.68
Lowest value of Va [pu]	1.007	1.007	1.007	1.009	0.985	0.970	0.946
Highest value of Va [pu]	1.053	1.091	1.091	1.088	1.093	1.111	1.107
Lowest value of Vb [pu]	0.983	0.998	0.998	0.968	0.934	0.932	0.891
Highest value of Vb [pu]	1.033	1.070	1.070	1.078	1.082	1.117	1.088
Lowest value of Vc [pu]	1.013	1.023	1.023	1.019	1.021	1.016	1.014
Highest value of Vc [pu]	1.051	1.073	1.073	1.073	1.073	1.073	1.073
Maximum VUF [%]	0.901	0.690	0.690	1.286	1.837	1.791	2.758

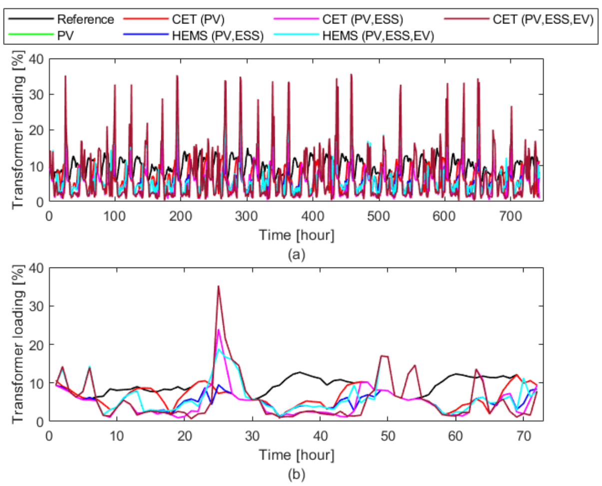

FIGURE 11. Transformer loading. (a) 1 month, (b) 3 days.

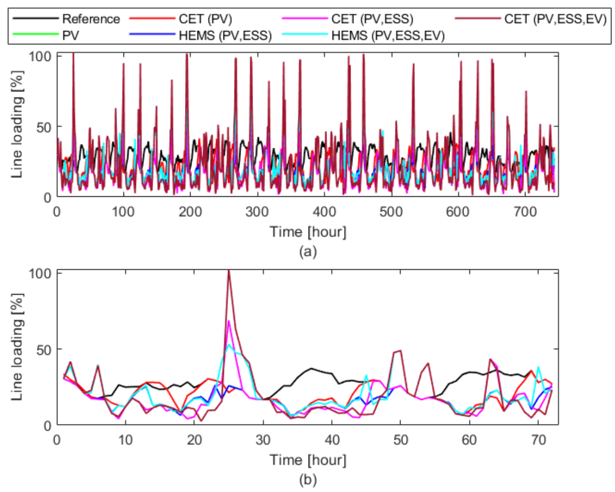

FIGURE 12. Line loading. (a) 1 month, (b) 3 days.

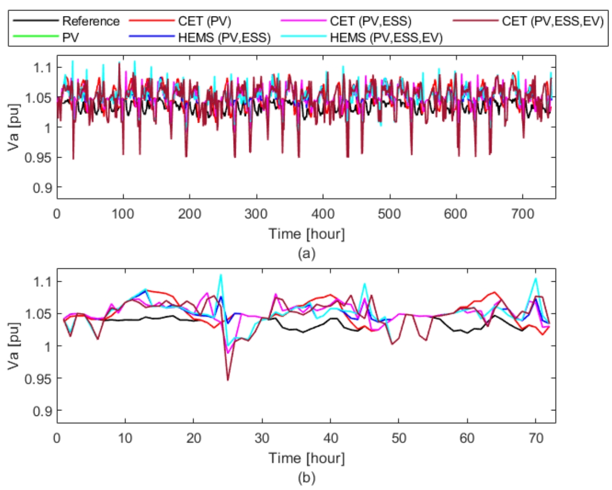

FIGURE 13. Phase a voltage (Va). (a) 1 month, (b) 3 days.

deviations at the LVDNs received considerable attention from researchers. The end nodes of the feeders usually have higher voltage deviation than other nodes that are near the transformer, especially in rural areas which have long feeders. The LVDNs could encounter a high voltage drop when the local demand is high and a voltage rise when the local generation is high. The LVDN voltage must be within 0.90 and 1.10 pu based on EN 50160. In this subsection, the impact of CET on voltage deviations at the end nodes of LVDN is assessed and compared with scenarios without CET. The voltage of each phase is presented separately since the studied LVDN is unbalanced, and each phase has different prosumers with different characteristics. The presented voltage is recorded at the connection point of load 53 which is located at the line end, and high voltage deviations are expected at this node. Table 6 and Figure 13-15 show that the CET scenarios resulted in higher voltage drops compared to HEMS. The voltage of phase b violated the voltage lower limit and recorded 0.891 pu for CET(PV, ESS, EV) scenario. This high voltage deviation happens when high energy is imported from the retailer to charge ESS and EVs at hours with low prices or to meet EVs mobility needs. The high energy flow results in a higher voltage drop on the lines impedances. The voltage of phase a violated voltage upper limit and recorded 1.111 pu for HEMS (PV, ESS, EV) scenario and 1.107 pu for CET (PV, ESS, EV) scenario. The voltage of phase b violated the voltage upper limit and recorded 1.11 pu for HEMS (PV, ESS, EV) scenario. This voltage rise results from simultaneous discharge of ESS and EVs.

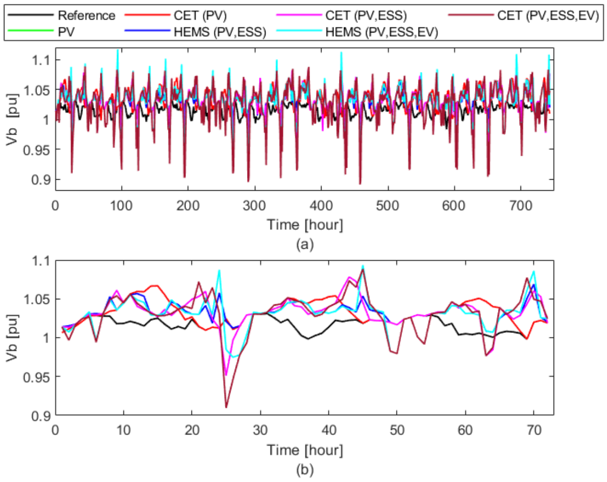

FIGURE 14. Phase b voltage (Vb). (a) 1 month, (b) 3 days.

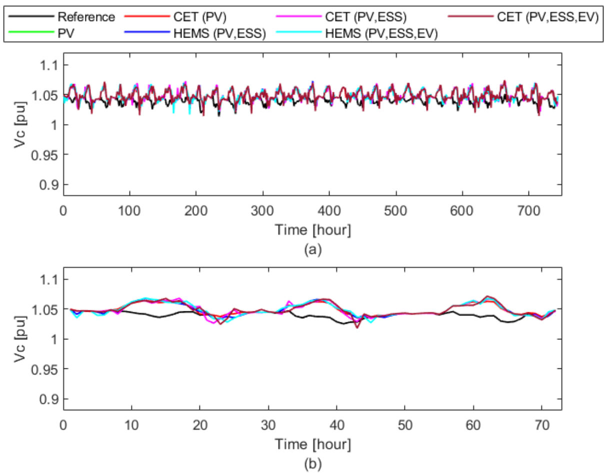

FIGURE 15. Phase c voltage (Vc). (a) 1 month, (b) 3 days.

3) IMPACTS ON PHASE UNBALANCE

In this subsection, the $VUF\%$ is calculated for the seven scenarios. Table 6 and Figure 16 show the $VUF\%$ values for the studied scenarios. The presented $VUF\%$ values are recorded at the connection point of load 53 that is located at the end of the line, and high voltage variations are expected at this node. For the scenarios without ESS or EV installation, $VUF\%$ remained below 1%. We can notice an increase in $VUF\%$ for scenarios with ESS or EV installation, especially CET(PV, ESS, EV) and CET(PV, ESS) scenarios. The $VUF\%$ for CET(PV, ESS, EV) exceeded the acceptable limit and reached 2.758%. This happens mainly due to charging ESSs and EVs simultaneously when electricity prices are low or to meet EVs mobility needs.. The $VUF\%$ for CET(PV, ESS) is slightly lower than the acceptable limit, and the maximum value reached is 1.837 %. HEMS(PV, ESS, EV) recorded 1.791 for $VUF\%$. In general. CET scenarios resulted in higher values of $VUF\%$ compared to the corresponding HEMS scenarios.

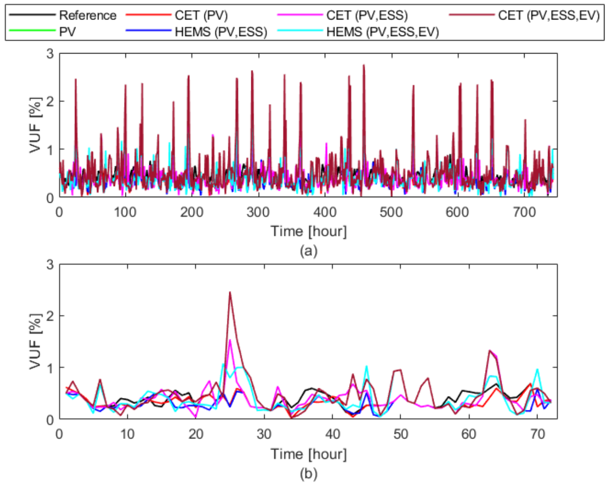

FIGURE 16. Voltage unbalance factor (VUF%) (a) 1 month, (b) 3 days.

4) COMPARISON OF THE IMPACTS OF DIFFERENT SCENARIOS USING BOXPLOT REPRESENTATION

Previous subsections provided a detailed analysis of the impacts of seven operational scenarios on LVDN. This section provides a statistical analysis of the transformer loading, lines loading, voltage deviations, and voltage unbalance for the simulation period (i.e., 1 month), as shown in Figure 17. For the CET (PV, ESS, EV) scenario with the highest impacts on the LVDN, the transformer loading is less than 20% for most of the hours during the month and has outliers with a maximum of 35.69. Similarly, the line loading is less than 57% for most of the month's hours and has outliers with a maximum of 102.68. The maximum limit is violated for only 4 hours during the whole month. The $VUF\%$ is less than 1.15% for most of the hours during the month, and it has outliers with a maximum of 2.758. The $VUF\%$ exceeded the maximum limit (i.e., 2%) for 23 hours during the whole month. As shown in Figure 13-15, the voltage at different phases is within the acceptable limits for most of the simulation period except for the voltage of phases a and b, which violated the limits for a few hours. The voltage of phase a exceeded the upper limit for 1 hour for the CET (PV, ESS, EV) scenario and for 6 hours for HEMS (PV, ESS, EV) scenario. The voltage of phase b exceeded the lower limit for 3 hours for the CET (PV, ESS, EV) scenario and exceeded the upper limit for 5 hours for HEMS (PV, ESS, EV) scenario.

Hence, comparing the HEMS and CET scenarios with the same resources, Figure 17 shows that the CET determines a greater loading level for transformers and lines and causes more intense and frequent voltage violations. Therefore, for the presented case, the CET mechanism is more prone to determine network constraints violation given the augmented magnitude of power flows within the network.

This study's results could be generalized to other cases with similar demand profiles, DER characteristics, and distribution networks. In other cases, CET could achieve better operation costs for the community than HEMS. However, the cost reduction will depend on the characteristics of loads,

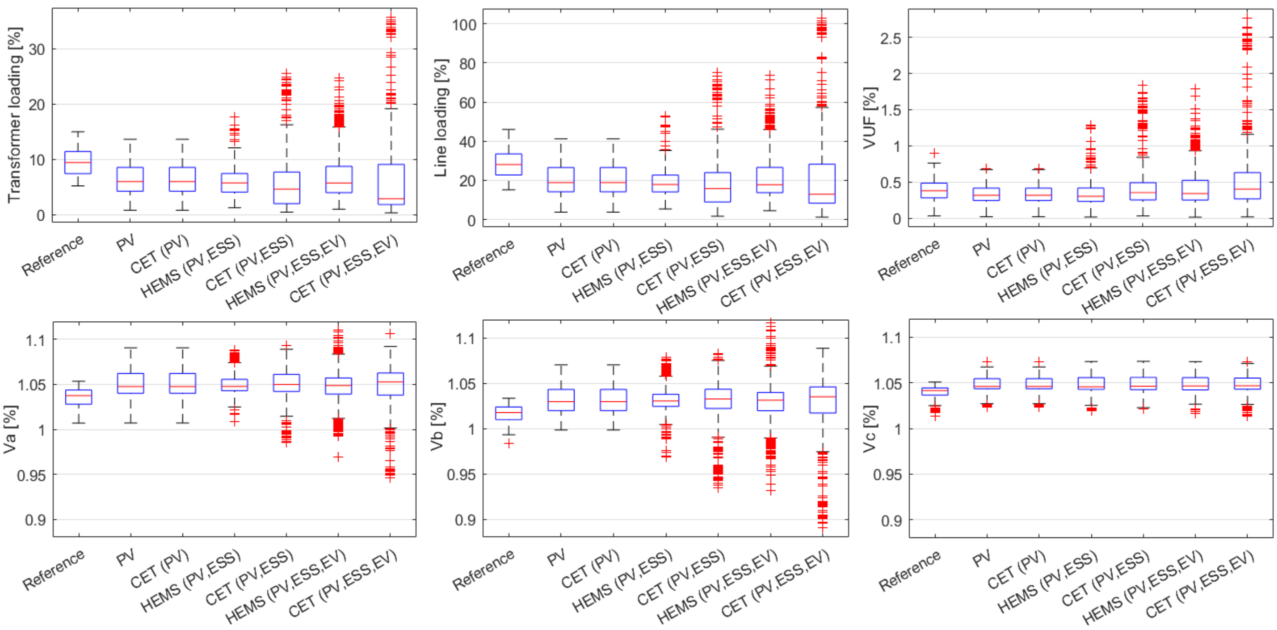

FIGURE 17. Comparison of the impacts of different scenarios using boxplot representation.

installed DERs, and pricing scheme. Due to the diverse characteristics of distribution networks (i.e., topology, type of loads, loading condition, DERs connected, etc.), future studies need to compare the impacts of CET on different distribution networks.

This study is useful for the planning phase of the distribution network to evaluate the benefits and challenges of the studied DERs management approaches (i.e., CET and HEMS). Based on the obtained results, policymakers can assess if the benefits of the proposed approach outweigh the challenges. Furthermore, the system operator can know the possible impacts on the distribution networks and if any infrastructure upgrades will be needed. In addition, it can be useful in the operation phase to evaluate the benefits and challenges of different DERs management approaches considering different operation scenarios, installed DERs, seasonal variations, and daily variations.

V. CONCLUSION

The distribution level of power systems is undergoing massive changes, and several types of distributed energy resources (DERs) are being installed. Many approaches have been developed for the efficient integration of DERs. The community energy trading (CET) approach was proposed recently for the coordinated management of DERs. However, the evaluation of CET benefits and its impacts on low voltage distribution networks (LVDN) require more research. Therefore, this article studied seven operation scenarios that consider the presence of different types of DERs and two DERs management approaches (i.e., CET and home energy management (HEMS)), considering a realistic Spanish case study.

The results showed the superiority of CET compared to HEMS in reducing the community's electricity cost, reducing energy bought from the retailer, and increasing self-consumption. However, for CET scenarios, there is an increase in peak demand of community energy imports from the retailer compared to HEMS. Moreover, the impacts of CET on the LVDN are assessed in comparison with HEMS, considering the same resources. The study showed that for CET scenarios, there is an increase in the loading of the transformer and lines. The transformer did not exceed the loading limits because of its high power rating compared to the aggregated demand. However, some lines exceeded their loading limits. Furthermore, CET determines the increase of the voltage drop at all phases and the voltage phase unbalance. The results showed that the reason for these impacts of CET is the simultaneous charging of community ESS and EVs when the electricity prices are low or to meet EVs mobility needs. The case study presented highlights that the adopted mechanism for energy trading has a non-negligible influence on the physical quantities exchanged by network users. Hence, given identical conditions in terms of resources, network constraints can be more likely violated depending on the mechanism adopted.

This study did not consider the uncertainties associated with demand profiles, photovoltaic (PV) generation, EVs arrival time, different EV types, etc. Future research will consider many uncertainties in the case study. Moreover, the CET behavior is significantly affected by the tariff design. Therefore, future research should study the impact of CET on LVDN, considering different tariff designs. Furthermore, due to the diverse characteristic of distribution networks (i.e., topology, type of loads, loading condition, DERs connected, etc.), Future studies should compare the impacts of community energy trading on different distribution networks.

TABLE 7. Comparison of the seven studied scenarios for January.

	No DERs	PV		PV+ESS		PV+ESS+EV	
	Reference	PV	CET	HEMS	CET	HEMS	CET
Imports from retailer (kWh)	58498.57	48503.58	41060.18	46524.57	40949.712	52236.36	45812.59
Exports to retailer (kWh)	0	9208.60	1373.43 (-85.09%)	6475.33	26.16 (-99.60%)	7546.58	135.32 (-98.21%)
Total local energy trading (kWh)	0	0	7835.16	0	12153.78	0	13615.13
Demand by retailer (%)	100	82.91	70.19	79.53	70	89.30	78.31
Demand by DERs (%)	0	17.09	29.81	20.47	30	10.70	21.69
Total operation Costs (€)	17050.43	12409.27	11773.45	11652.65	10789.19	12501.92	11511.31
CET cost reduction (%)	-	-	-5.12%	-	-7.41%	-	-7.92%
Costs of imports from retailer (€)	17050.43	14178.29	12041.08	12980.30	10794.18	14089.97	11542.63
Revenue of exports to retailer (€)	0	1769.02	267.63	1327.65	4.99	1588.05	31.32

APPENDIX

Table 7 compares the CET scenarios and other scenarios for winter (i.e., January). For all the studied scenarios, the introduction of CET significantly reduced the amount of energy sold to the retailer by up to 99% and increased community self-consumption by incentivizing local consumption to be covered through exchange between peers in the community. For CET scenarios, a negligible amount of energy is usually sold to the retailer. The producers prefer to sell excess energy to peers at a higher price than the retailer price, and the consumers prefer to buy energy from peers at a lower price than the retailer price. Therefore, most of the local generation was traded locally within the community when CET was introduced. However, for January, a lower percentage of demand was covered by DERs compared to July. This is due to the low PV production and high demand in January compared to July.

The results show an increase in the amount of traded energy between peers in the community when ESS and EV are installed because prosumers can charge ESS or EV when there is high PV generation and sell it at hours with less or no PV generation.

The results showed that DERs reduce the energy bought from the retailer and the electricity cost for the community. The CET scenarios reduced the community electricity cost compared to all the corresponding scenarios (i.e., with HEMS and the same DERs installed). CET reduced the community electricity cost by about 5% for CET (PV) scenario, 7% for CET (PV, ESS) scenario, and 8% for CET (PV, ESS, EV) scenario. CET scenarios recorded a lower cost reduction for January compared to July.

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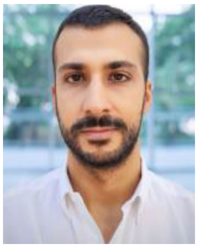

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