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Mitigating the Impacts of Community Energy Trading on Distribution Networks by Considering Contracted Power Network Charges

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ABSTRACT Driven by environmental and economic motives, different distributed energy resources (DERs) are being installed at a fast pace. The high penetration levels of DERs could result in technical issues at low voltage distribution networks (LVDNs) and lead to complex power system management. Therefore, many approaches were proposed in the literature to manage DERs to maximize their economic benefits while respecting the LVDNs' limits. One of the new approaches for managing DERs is community energy trading (CET). CET allows end users to exchange energy with each other besides energy exchange with retailers. Recent studies showed that CET could result in violations of the LVDNs limits if the grid constraints are not considered in the optimization model. These violations mainly happen due to the synchronized charging of electric vehicles and battery energy storage (i.e., flexible devices) connected to the LVDNs, which could require an infrastructure upgrade at LVDN. This paper proposes including contracted power cost in the CET objective function for energy cost minimization besides the energy cost to mitigate the impacts on LVDN. The proposed approach does not require the consideration of grid constraints in the CET model or interaction with the distribution system operator. The results showed that the proposed approach reduced the peak demand of the energy community (EC) by 34.3% without affecting its economic performance. Moreover, the proposed approach prevents violations of unbalanced LVDN limits in line loading, voltage unbalance, and voltage magnitude that occur in the CET scenario that does not consider contracted power cost.

INDEX TERMS Local electricity market, peer to peer energy trading, energy community trading, energy community, transactive energy, grid tariff, network tariff, demand charges, distributed energy resources.

I. INTRODUCTION

Renewable energy sources (RESs) are being deployed at a fast pace worldwide because of environmental challenges, government support, and RESs technological developments, which decreased their costs [1]. A considerable portion of the RESs are installed near end consumers with small capacities. Moreover, other flexible devices such as battery energy storage (BES) and electric vehicles (EVs) are being installed near end consumers. Small RESs, BES, EVs, etc., are usually called distributed energy resources (DERs). The high deployment of DERs at distribution networks brings many environmental benefits, like decreasing emissions of greenhouse gases, and economic benefits, like decreasing the electricity bills, while raising many economic and technical challenges [2], [3]. It is very complex to economically operate a massive number of DERs while respecting grid constraints, considering the low monitoring degree of distribution networks and lack of regulation devices. Therefore, there is a need for innovative management approaches to operate a large number of DERs efficiently to maximize the benefits of all stakeholders while maintaining grid stability and reliability besides eliminating or postponing infrastructure upgrades [4].

Community energy trading (CET) received considerable interest from academia and industry as a promising approach to effectively manage high penetration levels of DERs. CET allows end users to exchange energy with each other besides energy exchange with retailers. CET could reduce energy costs for the energy communities (ECs), reduce the locally generated renewable energy sold to the retailer by consuming it locally (i.e., increase self-generation), reduce energy imported from the retailer (i.e., increase self-sufficiency), and empower end-users to have a more active role in energy systems [5], [6]. Besides academic studies, many CET pilot projects were performed in several countries to study different market designs, different technologies, participants' behavior, etc. [7].

Compared to the market design and evaluation of enabling technologies, the impacts of CET on low voltage distribution networks (LVDNs) received little interest in existing literature and pilot projects. Few studies assessed the impacts of CET on LVDN if the grid constraints were not included in the model. These studies assessed the impacts of CET on different components and operation limits of LVDNs, such as peak demand, losses, voltage deviations, congestions of distribution network components, and voltage unbalance [6], [8]–[14]. The results of these studies showed that under low DER penetration levels and low local energy trading, no violations of grid constraints occur. However, some constraints are violated under high DER penetration levels and high local energy trading.

Several approaches were investigated in existing literature to avoid violations of grid limits in CET. Previous studies used sensitivity coefficients [15], DC load flow equations [16], [17], or AC load flow equations [18] for network limits consideration in the model. By doing so, the operation of LVDN within limits is usually guaranteed. All of these techniques, however, have inherent drawbacks [10]. The sensitivity coefficients, for example, approximate the actual grid. DC load flow is better suited for transmission networks but inaccurate at the distribution networks [19]. Due to the non-linear nature of load flow equations, AC load flow requires a higher computation power than the other approaches, and the optimal solution cannot be ensured due to the non-convexity of the optimization problem. Previous research also proposed signals of network charges, dynamic pricing, and power losses to reflect grid limits [20]. Nevertheless, according to [21], only 20% of the examined articles adequately represented grid limits in the market models of CET. So, further study is required to create effective approaches with low computational complexity that mitigate the impacts of CET on LVDNs.

The grid tariffs are flat energy-based in most countries. Flat energy-based grid tariffs do not incentivize end users to decrease their peak demand because they are charged on the used energy, not the rate of energy use [22]. However, grid investments are mainly associated with maximum peak utilization [23]. Few countries introduced power-based grid tariffs to recover grid costs. Therefore, efficient energy and peak coincident grid tariff design could be a feasible approach for decreasing the impacts of local energy trading on distribution networks and postponing infrastructure upgrades [24]. Few studies investigated the effectiveness of considering peak demand or its cost (i.e., contracted power costs, power-based network charges, or demand charges) in the local energy trading model. Contracted power costs are common for industrial and commercial consumers in many countries, such as Norway, which has charges based on the peak demand during the month [25]. However, it is rarely applied to residential consumers [26].

Local energy trading between five industrial buildings in Norway was evaluated in [25]. The study considered the costs of energy and contracted power. The community contains combined heat and power (CHP), PV, shared BES, EVs, and controllable loads. The findings showed the effectiveness of synergies between local energy trading and contracted power costs in decreasing the costs of industrial EC compared to individual scheduling of buildings. Another study compared the effect of energy-based and power-based grid tariffs on the peak demand of EC in Norway, containing pre-school, grocery store, and 28 houses [27]. The EC houses have PV, BES, unidirectional EVs, and controllable water heaters, enabling local energy trading between EC participants. Each house has a different DERs, but all of them have water heaters. The findings showed the effectiveness of power-based grid tariffs in decreasing the peak demand of EC at critical hours over energy-based grid tariffs.

Ref. [23] conducted a similar study for one week for a smaller EC in Norway. However, the local market enables trading of the contracted power between EC participants besides energy trading. The results proved the effectiveness of the local market and contracted power in decreasing the EC peak demand and decreasing the cost of EC and individual participants. The authors of [28] studied the effect of grid tariff design on the peak demand of a local electricity market for residential and commercial buildings in Germany, considering current and future scenarios of networks, loads, and installed DERs. The buildings contain PV, BES, HP, or EVs. The results showed that power-based grid tariffs are more effective than energy-based grid tariffs in decreasing peak demand and changing the behavior of flexible devices to shift their demand to low-demand hours. The authors of [29] studied the effect of grid tariffs on the operation of CET for case studies in Ireland, Norway, and Austria. In Ireland, the electricity prices have an energy-based grid tariff component in a static time of use tariff. The study showed the viability of CET in decreasing energy imports/exports from/to retailer. The Norwegian case study analyzed the effect of the grid tariff component in retailer price on the operation of a community of industrial buildings similar to what is studied in [25]. The findings showed that grid tariff is more effective in decreasing the costs of peak demand and energy in CET than without adopting CET. The Austrian case study analyzed the effect of grid tariffs applied for local trade within EC. The results showed that a grid tariff design that favors trading between customers connected to the same feeder could maximize the trade between nearby customers. Another study found that using a discriminatory grid tariff based on zones or distance between peers in local energy trading could decrease the stress in the grid [30]. Table 1 compares this study with relevant studies.

These studies did not assess the impacts on distribution networks when local energy trading and contracted power are considered. Moreover, the studies focused on tariff designs in a few countries. Therefore, the impacts of local energy trading and contracted power costs on distribution networks considering pricing schemes of other countries should be studied since every country has different tariff designs.

To the best of our knowledge, this is the first study that proposes including contracted power costs in the CET objective function besides the energy cost to mitigate the impacts of CET on unbalanced LVDN besides a techno-economic analysis considering a Spanish case study with real demand measurements and electricity prices (i.e., energy and contracted power). The study analyzes EC behavior, considering efficient tariff designs rather than considering distribution network constraints. The proposed approach does not require the consideration of grid constraints in the CET model. Therefore, it has low computational costs. Moreover, it does not require any interactions with DSO while preserving CET economic performance. The contributions of this study are:

- Add the contracted power cost besides energy cost in the CET objective function for energy cost minimization based on the current charges in Spain for residential consumers. Then, compare its performance with the CET model that considers energy cost and energy-based grid tariff in the objective function.
- Assess the impacts of CET (with/without contracted power consideration) on unbalanced LVDN in the presence of heterogenous DERs like PV, BES, and EVs.
- Evaluate the impacts of CET on LVDN line loading, transformer loading, voltage unbalance, and voltage magnitude by considering the contracted power cost and without considering the grid constraints in the optimization model or interaction with the distribution system operator (DSO).

This paper is organized as follows. Section II presents the EC optimization model, modeling of LVDN, DERS, energy prices, and contracted power prices. Section III presents the results of the techno-economic comparison of studied scenarios. Section IV presents the impacts of CET on LVDN. The conclusion is provided in section V.

II. PROBLEM FORMULATION

This section presents EC modeling. Moreover, it introduces grid characteristics, deployed DER specifications, electricity prices, and contracted power costs. Furthermore, it describes the studied scenarios.

This study is divided into two cascaded phases. The first phase executes a CET optimization of the studied EC, resulting in the energy dispatch of houses for the study period T (i.e., one month). Every 1 hour interval t, participants' decisions are optimized. The market model is created using MATLAB. The second phase involves performing a load flow to assess the effects on the LVDN based on the first phase outcomes. Pandapower software is used for executing load flow [31], [32]. Figure 1 depicts a schematic layout of the assessment procedure of CET impacts on LVDN. As inputs, the MATLAB EC model (first phase) gets DERs characteristics, electricity prices, contracted power prices, PV profiles, and load profiles. The first phase output is the net demand for each house that is required for load flow. LVDN data and houses net demand are inputs to Pandapower (second phase), which performs 3-phase load flow. The definition of variables, parameters, scalars, and sets are given in the appendix.

A. MODELING OF ENERGY COMMUNITY

The EC objective function is bound by DERs operating limits (1)-(9), power balance limits (10), EC local trading (i.e., P2P-ET) limits (11)-(14), and contracted power limits (15)-(16). The deployed BES must function between its limits. The power capacity of the BES charger limits the discharging $D_{t,h}^{\mathrm{BES}}$ and charging $C_{t,h}^{\mathrm{BES}}$ power of BES. Zero is the lower bound for discharging and charging powers. $\bar{D}_{BES}$ and $\bar{C}_{BES}$ are the upper bounds of discharging and charging powers, respectively, as stated in (1) and (2). Furthermore, energy stored in BES $E_{t,h}^{\mathrm{BES}}$ in kWh has upper and lower bounds, as stated in (3). The BES state of charge (SoC) lower and upper bounds are 20% and 100%, respectively.

Equation (4) calculates the amount of stored energy at every BES $E_{t,h}^{\mathrm{BES}}$ in a time t for a house h. Where, η_C^{BES} is charging efficiency and η_D^{BES} is discharging efficiency of BES. The energy stored at BES at time instant $t-1$ is designated as $E_{t-1,h}^{BES}$. On the first day of the studied period, the initial SoC of any BES is a random value between 20% SoC and 80% SoC. The final values of the BES SoC on the first day are used as the SoC of the first hour on the second day. Every other day of the simulation period is analogous in this regard.

$$0 \leqslant D_{t,h}^{\mathrm{BES}} \leqslant \bar{D}_{BES} \qquad \forall t \in T, \forall h \in H \tag{1}$$

$$0 \leqslant C_{t,h}^{\mathrm{BES}} \leqslant \bar{C}_{BES} \qquad \forall t \in T, \forall h \in H \tag{2}$$

$$\underline{E}_{BES} \leqslant E_{t,h}^{\mathrm{BES}} \leqslant \bar{E}_{BES} \qquad \forall t \in T, \forall h \in H \tag{3}$$

$$E_{t,h}^{\mathrm{BES}} = E_{t-1,h}^{\mathrm{BES}} + \eta_C^{BES} \times C_{t,h}^{\mathrm{BES}} - \left(\frac{1}{\eta_D^{BES}}\right) \times D_{t,h}^{\mathrm{BES}} \qquad \forall t \in T, \forall h \in H \tag{4}$$

Similarly, the deployed EV must function between its limits. The EV discharging power $D_{t,h}^{\mathrm{EV}}$ and charging power $C_{t,h}^{\mathrm{EV}}$ are bounded by the bidirectional EV charger power capacity that links the EV to the grid. Zero is the lower bound for both

TABLE 1. Comparison of relevant studies that considered impacts of CET on LVDNs or power-based grid tariff in CET.

Ref.	Data	Study period	Evaluated impacts	voltage unbalance	DERs	G2V	V2G	Contracted power	Impacts mitigation
[6]	Spain	1 month July	Peak demand, components loading, voltage	✓	PV, BES, EV	✓	✓	X	X
[8]	England	1 day	Voltage, losses, peak demand	✓	PV, EV	✓	X	X	X
[9]	Ireland	January, June	Voltage	X	PV, BES	X	X	X	X
[10]	Ireland	January, June	Voltage, Losses	X	PV, BES	X	X	X	X
[11]	Ireland	January, June	Losses, voltage	✓	PV, BES	X	X	X	X
[12]	Norway	21 days (summer)	Voltage, losses, peak demand,	X	PV, BES/EV	✓	X	X	X
[13]	Australia	1 day	Voltage, Losses	X	PV, BES, controllable loads	X	X	X	X
[14]	England	1 month	Voltage	X	PV, WG, BES, EV	✓	✓	X	X
[23]	Norway	1 week	X	X	PV, BES	X	X	✓	X
[25]	Norway	1 year	X	X	CHP, PV, BES, EVs, controllable loads	✓	✓	✓	X
[27]	Norway	1 year	X	X	PV, BES, EV, water heater	✓	X	✓	X
[28]	Germany	1 year	X	X	PV, BES, HP, EV	✓	X	✓	X
This study	Spain	1 month July	Peak demand, components loading, voltage	✓	PV, BES, EV	✓	✓	✓	✓

discharging and charging powers. $\bar{D}_{EV}$ and $\bar{C}_{EV}$ refer to the EV upper bounds of discharging and charging powers, respectively, as stated in (5) and (6). Moreover, energy stored in EV $E_{t,h}^{\mathrm{EV}}$ in kWh has upper and lower bounds, as stated in (7) [25].

The status of EV (i.e., connected to the charger or not) at the time t is defined by a binary parameter b_t, as stated in (8). $b_t = 1$ when the EV is connected to the charger and $b_t = 0$ when the EV is not connected to the charger. Equation (9) calculates the amount of energy stored at every EV $E_{t,h}^{\mathrm{EV}}$ in a time instant t for a house h. Where η_C^{EV} is charging efficiency and η_D^{EV} is discharging efficiency of EV. The energy stored at EV at time instant $t-1$ is designated as $E_{t-1,h}^{\mathrm{EV}}$. On the first day of the studied period, the initial SoC of any EV is a random value between 20% SoC and 80% SoC. The final values of the EV SoC on the first day are used as the SoC of the first hour on the second day. Every other day of the simulation duration is analogous in this regard.

It is assumed that the EVs are linked to the LVDN for charging/discharging from hour 17 in one day to hour 8 of the next day and are utilized for mobility throughout the other day's hours. When an EV is utilized for mobility, the SoC of the battery drops. When the EV begins charging, the initial SoC relies on the SoC when the vehicle is unplugged from the LVDN and the distance traveled. It is estimated that the SoC of the EV battery will stay between 20% and 100% when it is linked to the charger. To ensure that EV owners' mobility and comfort requirements are met, the SoC of the EV battery at 8 (i.e., departure time) must be greater than or equal to 75%. At every house node, the supply must equal demand at every time t, as stated in the power balance constraint (10). This equation changes depending on the installed DERs at every house.

$$0 \leqslant D_{t,h}^{\mathrm{EV}} \leqslant \bar{D}_{EV} \times b_t \qquad \forall t \in T, \forall h \in H \tag{5}$$

$$0 \leqslant C_{t,h}^{\mathrm{EV}} \leqslant \bar{C}_{EV} \times b_t \qquad \forall t \in T, \forall h \in H \tag{6}$$

$$\underline{E}_{EV} \leqslant E_{t,h}^{\mathrm{EV}} \leqslant \bar{E}_{EV} \qquad \forall t \in T, \forall h \in H \tag{7}$$

$$b_t = \begin{cases} 1, & if\ EV\ is\ connected\ to\ the\ LVDN\ at\ time\ inst \\ 0, & otherwise \end{cases} \quad \forall t \in T \tag{8}$$

$$E_{t,h}^{\mathrm{EV}} = E_{t-1,h}^{\mathrm{EV}} + \eta_{EV}^{c} \times C_{t,h}^{\mathrm{EV}} \Delta t - \left(\frac{1}{\eta_{EV}^{d}}\right) \times D_{t,h}^{\mathrm{EV}} \Delta t \qquad \forall t \in T, \forall h \in H \tag{9}$$

$$G_{t,h} + I_{t,h} + P_{t,h}^{PV} + D_{t,h}^{\mathrm{BES}} + D_{t,h}^{\mathrm{EV}} = X_{t,h} + dem_{t,h} + F_{t,h} + C_{t,h}^{\mathrm{BES}} + C_{t,h}^{\mathrm{EV}} \qquad \forall t \in T, \forall h \in H \tag{10}$$

Within the EC, the purchase of house h from peer p equals the export of p to h at every time t taking into account the losses at LVDN because of P2P-ET, as stated in (11). μ^{loss} refers to the LVDN energy losses because of P2P-ET. P2P-ET within the EC results in 5% energy losses (i.e., $\mu^{loss} = 0.95$). Each house with DERs is able to export energy to any house (i.e., peer) in the EC. The total energy exported $X_{t,h}$ from house h at time t is the sum of exported energy $X_{t,h\rightarrow p}^{p}$ from house h to peer p, as stated in (12).

In a similar way, the total energy imported $I_{t,h}$ by house h at time t is the sum of imported energy $I_{t,h\leftarrow p}^{p}$ by house h from peer p, as stated in (13). Since P2P trading takes place inside the EC, the sum of houses energy sales and purchases must

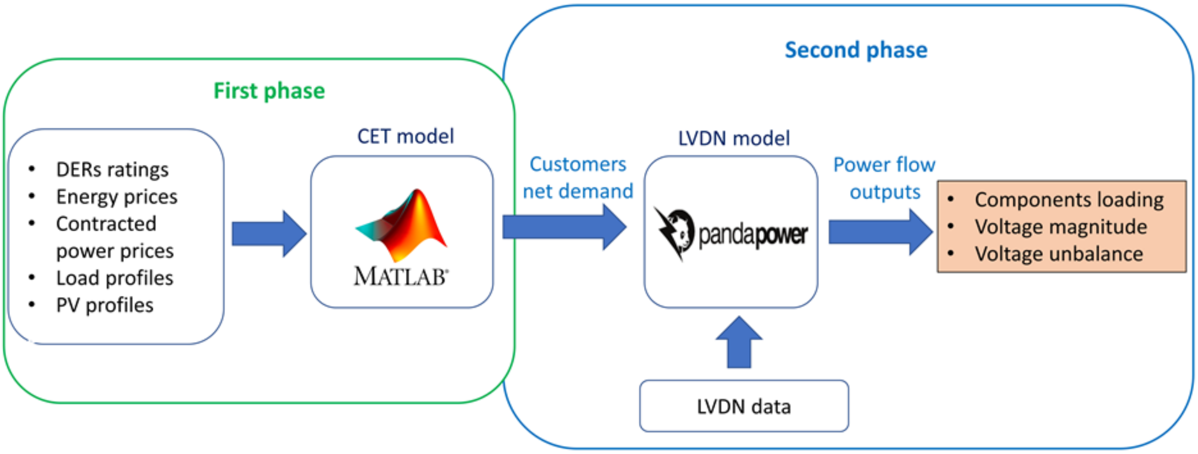

FIGURE 1. Schematic layout of the assessment procedure of CET impacts on LVDN.

equal each other, taking into account the losses at LVDN because of P2P-ET, as stated in (14).

$$I^{p}_{t,h\leftarrow p} = \mu^{loss} \times X^{p}_{t,p\rightarrow h} \qquad \forall p \neq h, \forall t \in T, \forall h \in H \tag{11}$$

$$X_{t,h} = \sum_{p\neq h} X^{p}_{t,h\rightarrow p} \qquad \forall t \in T, \forall h \in H \tag{12}$$

$$I_{t,h} = \sum_{p\neq h} I^{p}_{t,h\leftarrow p} \qquad \forall t \in T, \forall h \in H \tag{13}$$

$$\sum_{h} \mu^{loss} \times X_{t,h} = \sum_{h} I_{t,h} \qquad \forall t \in T \tag{14}$$

The energy purchased from the retailer by all houses in the EC must be less than or equal to the contracted power at any hour of the day, as stated in (15). Similarly, the energy sold to the retailer by all houses in the EC must be less than or equal to the contracted power at any hour of the day, as stated in (16).

$$\sum_{h\in H} G_{t,h} \leq CP_{per} \qquad \forall per \in P, \forall t \in T \tag{15}$$

$$\sum_{h\in H} F_{t,h} \leq CP_{per} \qquad \forall per \in P, \forall t \in T \tag{16}$$

B. MODELING OF LVDN, DERS, ENERGY PRICES, AND CONTRACTED POWER PRICES

This section provides an overview of the LVDN that is utilized as a case study. Furthermore, it presents the characteristics of the loads and DERs. In addition, it discusses the energy selling/purchasing prices to/from the energy retailer and contracted power costs in Madrid, Spain.

The test network is a commonly used IEEE European test system for DERs management research [33]. It has an 800 kVA transformer with 11 kV primary and 0.416 kV secondary. It has radial low voltage feeders supplying 55 houses. Each house has a unique connection point. Phase A has 21 houses connected, phase B has 19 houses connected, and phase C has 15 houses connected. Figure 2 illustrates the single-line diagram of the distribution network. Where the color of the house number indicates the phase of connection of that house, and the circle color indicates the installed DERs at the house.

The profiles are anonymized real measurements for customers in Madrid, Spain, given by i-DE, an Iberdrola Group DSO. Each consumer has a unique consumption profile, chosen randomly from the measurements collected from Madrid residents. The load profiles in this study have a 1-hour resolution. The market model solely examines active power trading and ignores reactive power. As a result, the loads in the load flow are considered to have a fixed power factor of 0.95 pu. This study is particularly pertinent in the European scene since policymakers support forming ECs that install DERs and local energy exchange. Various legal and functional bodies, such as the Citizen Energy Community (Directive 2019/944) and the Renewable Energy Community (Directive 2018/2001), are being established.) [34], [35]. The

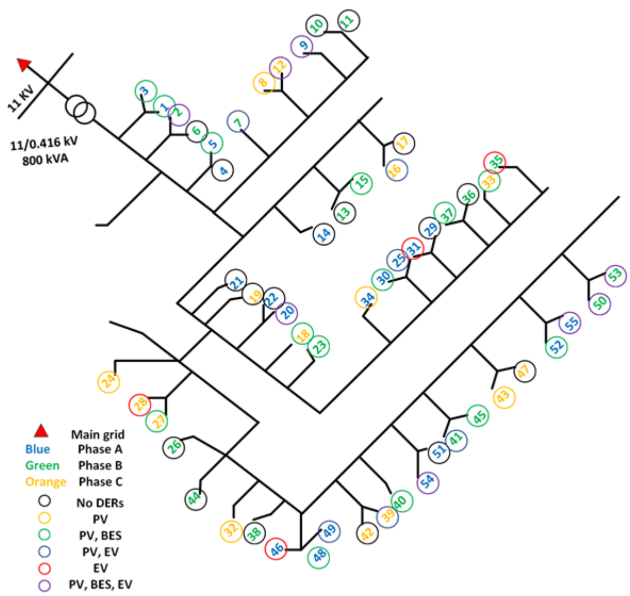

FIGURE 2. Single line diagram of the low voltage test system.

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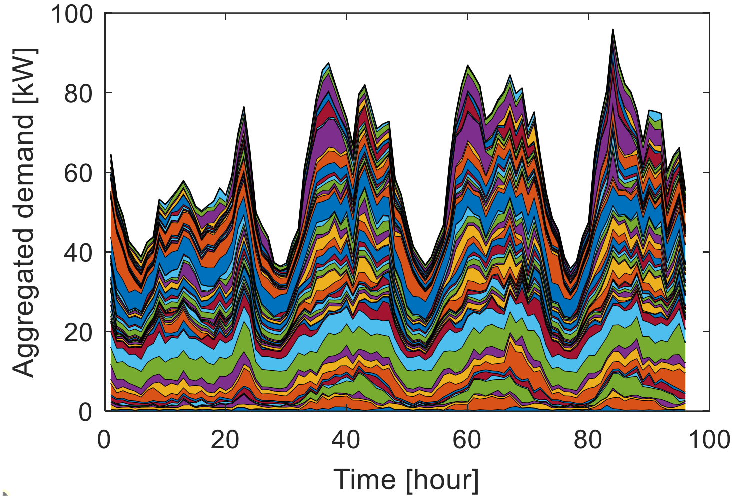

FIGURE 3. **Houses aggregated demand for four days.**

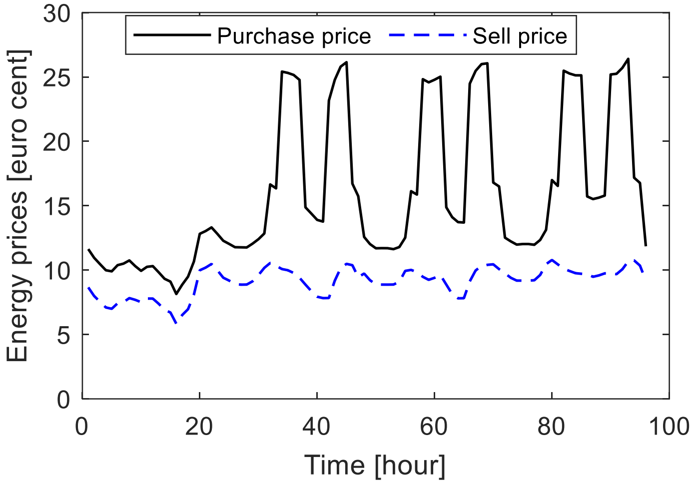

FIGURE 5. **Energy purchase and sell price for four days.**

aggregated demand of the 55 houses for four days is depicted in Figure 3.

PV, BES, and EV are among the DERs connected to the investigated LVDN. Any customer can have one or more of these DERs, while some users do not have any DERs present. The installed PV at any house has a power rating of 5 kWp. In the EC, 33 PV systems have been deployed (representing 60% of the houses). PV generation profiles for Madrid, Spain, are acquired from Renewables Ninja [36]. Figure 4 depicts the PV generation of a single house with PV installation.

The BES energy and power capacities are 13.5 kWh and 5kW, respectively, and the discharging and charging efficiencies are 95%. In the EC, 22 BES are deployed (representing 40% of houses). As in Nissan leaf, EVs have a battery with 24 kWh energy capacity and a 3.6 kW charging rate. The efficiency of discharging and charging for EVs is 96%. The chargers of EVs enable energy injection (V2G) or absorption (G2V). In the EC, 18 EVs have been deployed (representing 33% of houses). All houses with PV, BES, or EV installation are assumed to have the same DER characteristics.

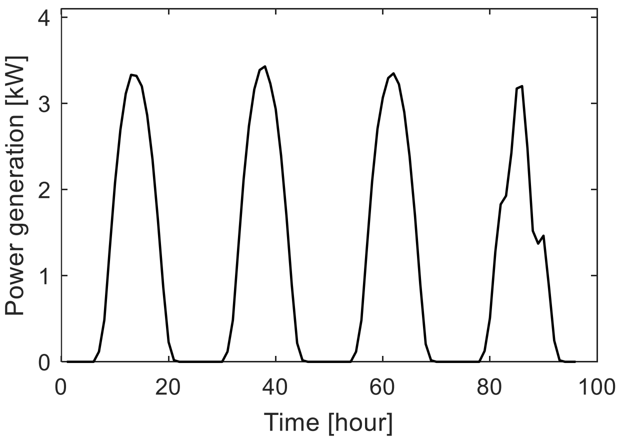

FIGURE 4. **PV production for a single house in four days.**

The Spanish pricing for selling or purchasing energy to/from the retailer is utilized in this analysis. The purchasing and selling prices in Madrid for July 2021 are acquired from the Spanish TSO Red Eléctrica [37]. In Spain, a 5 % tax is added to the import prices of Red Eléctrica. The energy purchase and selling prices are depicted in Figure 5. The first day has low prices because it is a weekend day (i.e., Sunday), and the other days are weekdays.

The contracted power cost for the considered consumers is divided into two periods. Period 1: from 8 a.m. to midnight, which has a high price for contracted power (i.e., peak hours). Period 2: from midnight to 8 a.m., which has a low price for contracted power (i.e., off-peak hours). The contracted power for period 1 must be greater than or equal to the contracted power for period 2, as stated in (17). Table 2 presents the contracted power cost and its components in Madrid, Spain. Policy costs represent Spanish islands' extra costs, RES support, among others. A 5 % tax is added to the contracted power costs. In practice, the houses have the option of surpassing the contracted power and paying a penalty. It is assumed for simplicity that the contracted power cannot be surpassed.

TABLE 2. **Contracted power costs in Madrid, Spain.**

Contracted power costs	Period 1 (Peak)	Period 2 (Off-peak)
Transmission and distribution costs (€/kW)	23.469833	0.961130
Policy costs (€/kW)	4.970533	0.319666
Total costs with a 5% tax (€/kW)	**29.8623843**	**1.3448358**

TABLE 3. Techno-economic comparison of the studied scenarios.

	CET without CP (scenario one)	CET with CP (scenario two)
Imports from retailer (kWh)	26485.69	26449.65
Exports to retailer (kWh)	758.64	776.26
Total local energy trading (kWh)	17329.93	16881.14
Demand by retailer (%)	56.08	56
Demand by DERs (%)	43.92	44
Peak of grid consumption (kW)	234.32	153.96
Total operation Costs (€)	3485.35	3513.81
Costs of imports from retailer (€)	3541.81	3572.04
Revenue of exports to retailer (€)	56.46	58.23

$$CP_1 \geq CP_2 \tag{17}$$

C. STUDIED SCENARIOS

The findings of a previous study [6] showed that local energy trading within EC containing high PV, BES, and EV penetration caused violations in the unbalanced LVDN under study in lines loading, voltage deviations, and voltage unbalance. These violations mainly happen due to the synchronized charging of EVs and BES (i.e., flexible devices) to take advantage of the retailer's low energy prices. Similarly, the violations could happen due to the synchronized discharging of EVs and BES (i.e., flexible devices) to fulfill the EC demand at hours with high retailer energy prices.

This study proposes including contracted power costs (i.e., power-based grid tariff) in the EC objective function besides the energy cost to mitigate the impacts on LVDN. This proposal aims to decrease the impacts on LVDN without considering the grid constraints in the optimization model. This results in a lower computational power requirement and no interaction with DSO.

In this study, two scenarios are compared. In scenario one, which represents CET without contracted power, the objective of EC is minimizing the expenses of EC energy purchased from the retailer while maximizing the revenue generated from selling the EC energy excess to the retailer, as stated in (18). In scenario two, which represents CET with contracted power, the objective of EC is minimizing contracted power cost and the expenses of EC energy purchased from the retailer while maximizing the revenue generated from selling the EC energy excess to the retailer, as stated in (19). Where p_{per}^{cp} is contracted power price for period per and CP_{per} is the contracted power at period per. To have a fair comparison between the two scanrios, the cost of contracted power per day in scenario two is represented

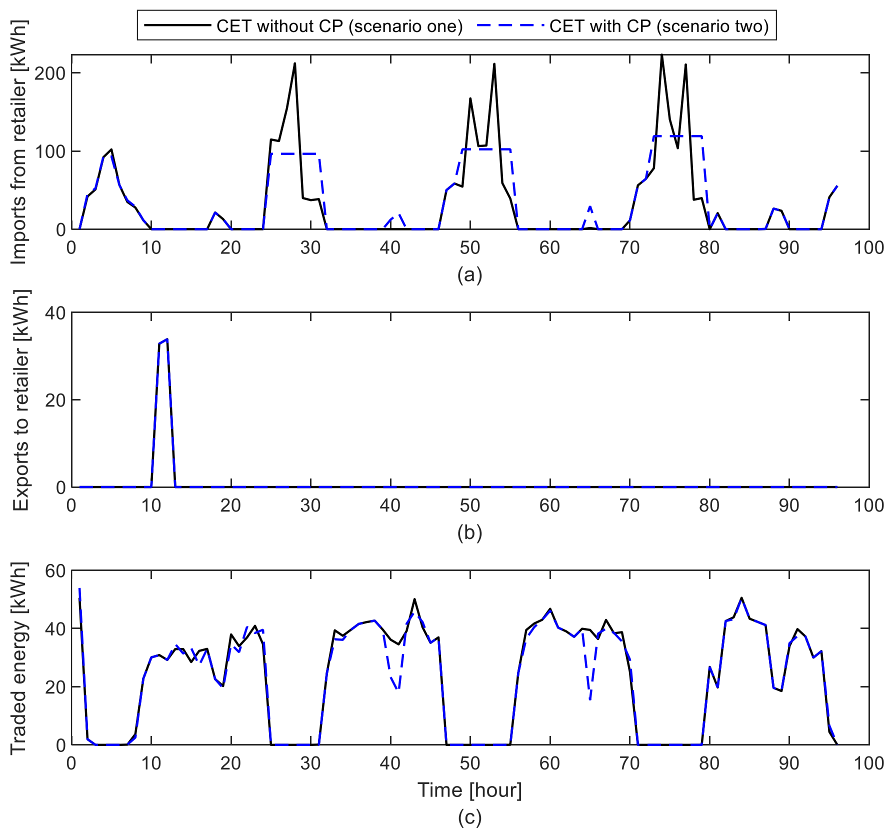

FIGURE 6. Interaction with the retailer and traded energy within EC for four days.

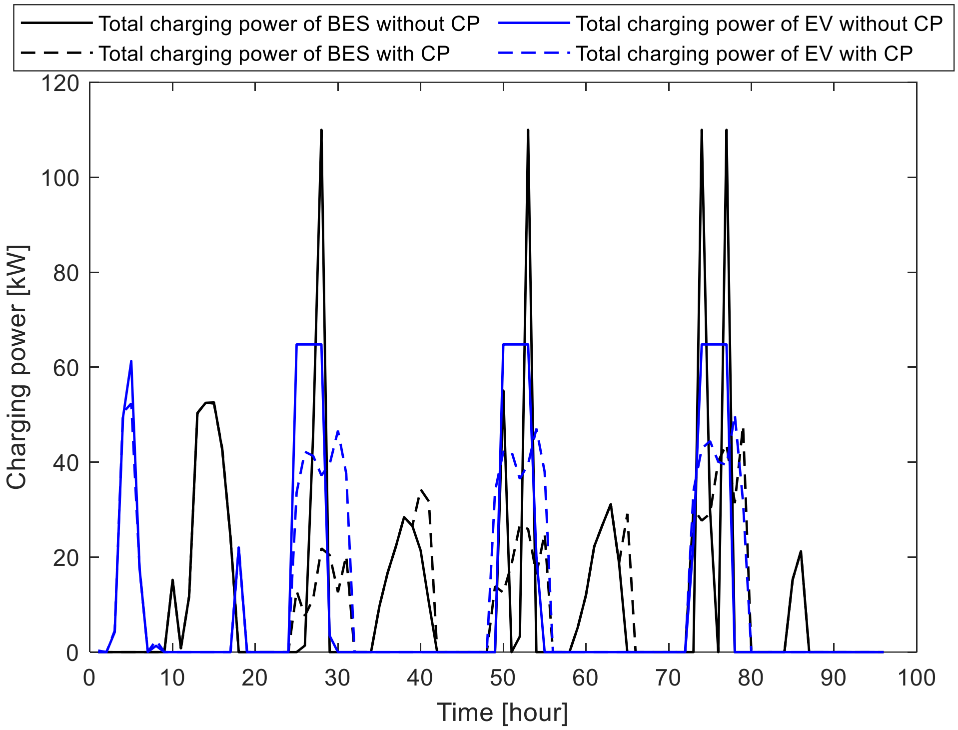

FIGURE 7. The aggregated charging powers of BES and EVs for four days.

as energy cost (i.e., volumetric term) in €/kWh and added to the energy import price used in scenario one.

$$min \sum_{t} \sum_{h} (p_t^b \times G_{t,h} - p_t^s \times F_{t,h})) \quad (18)$$

$$\min \left(\sum_{per \in P} p_{per}^{cp} \times CP_{per} + \sum_{t} \sum_{h} (p_t^b \times G_{t,h} - p_t^s \times F_{t,h}) \right) \quad (19)$$

III. TECHNO-ECONOMIC EVALUATION OF THE TWO STUDIED SCENARIOS

This section presents a techno-economic evaluation and comparison of the studied scenarios. Table 3 shows a comparison between scenario one for CET without contracted power and scenario two for CET with contracted power. It can be noted that interaction with the retailer regarding energy purchased by EC and energy sold by EC from/to the retailer is approximately identical for both scenarios. Moreover, scenario one has a slightly higher energy traded within the EC than scenario two. Furthermore, the percentage of demand covered by the retailer and EC DERs are the same in both scenarios. Similarly, the EC net operation cost, energy purchased from retailer cost, and energy sold to retailer revenues are approximately identical. The results show a very similar performance of the studied scenarios. However, the table indicates that scenario two reduced the EC peak demand by 34.3% compared to scenario one.

Figure 6 displays the interaction with the retailer regarding the sum of energy purchased by EC houses from the retailer, the sum of energy sold by EC houses to the retailer, and the sum of energy traded between houses within the EC for four days. Figure 6(a) demonstrates that scenario one has a significantly larger peak in the energy purchased from the retailer than scenario two, when the EC objective function considers the contracted power cost. Moreover, there are many hours with no energy purchase from the retailer in both scenarios. During these hours, the EC houses cover their demand with their DERs or other houses in EC that have surplus energy and exchange it locally within the EC. This shows that CET increases the independence of EC from the retailer for both scenarios.

Figure 6(b) demonstrates an identical behavior of the two studied scenarios, where the EC houses sell a tiny quantity of energy to the retailer in a few hours of the displayed days. Furthermore, for most hours, no energy is sold to the retailer. This shows that CET and flexible devices (i.e., BES and EVs) increase self-generation by consuming the generation of EC RESs locally within the EC. Similarly, Figure 6(c) demonstrates an identical amount of energy traded locally within the EC for both scenarios. The local trade of energy occurs mostly at hours with high PV generation (i.e., daytime hours) and night hours using the energy stored in flexible devices (i.e., BES and EV) deployed in the EC.

The aggregated charging powers of BES and EVs are presented in Figure 7 to analyze the reason for the higher peak demand in scenario one compared to scenario two. In scenario one, there is no limit on the peak of energy purchased/sold from/to the retailer. Therefore, there are hours with very high charging power due to the synchronized charging of most BES or EVs deployed in the EC to benefit from the low retailer prices at certain day hours or fulfill EVs' mobility needs.

However, in scenario two, the sum of charging powers is limited because the contracted power of the EC limits the peak of energy purchased from the retailer or sold to the retailer at any hour of the day. BES and EVs charge in more hours in scenario two than in scenario one since they do not charge at the maximum charging power to respect the contracted power constraint.

IV. IMPACTS OF STUDIED SCENARIOS ON LOW VOLTAGE DISTRIBUTION NETWORK

The net power demand of each house in the EC is determined from the first phase of the study (i.e., CET optimization), as stated in (19). $P_{t,h}^{d}$ is used as input to Pandapower software to run 3-phase load flow [32], [38]. The impacts of CET on LVDN line loading, transformer loading, voltage unbalance, and voltage magnitude at all phases are evaluated for the two scenarios. The voltage unbalance factor (VUF) is determined as stated in (20) according to IEC [31]. The VUF maximum allowed value is 2%. Where V_2 is negative sequence component, and V_1 is positive sequence component.

$$P_{t,h}^{d} = G_{t,h} + I_{t,h} - F_{t,h} - X_{t,h} \tag{19}$$

$$VUF\% = \frac{V_2}{V_1} \times 100 \tag{20}$$

Table 4 summarizes the impacts of CET scenario one (i.e., CET without CP) and scenario two (i.e., CET with CP) on LVDN. It demonstrates the maximum loading of the line, maximum loading of the transformer, maximum VUF, and maximum/minimum values of phase voltage.

TABLE 4. An overview of the impacts of CET on the studied distribution network.

	CET without CP (scenario one)	CET with CP (scenario two)
Max. loading of line [%]	106.76	74.15
Max. loading of transformer [%]	37.02	24.56
Max. VUF [%]	2.84	1.93
Max. value of Va [pu]	1.095	1.091
Min. value of Va [pu]	0.944	0.960
Max. value of Vb [pu]	1.081	1.093
Min. value of Vb [pu]	0.893	0.934
Max. value of Vc [pu]	1.078	1.078
Min. value of Vc [pu]	1.016	1.013

A. LOADING OF LINES AND TRANSFORMER

The lines of the studied LVDN have the same capacity. Therefore, the lines supplying a few houses are lightly loaded. However, the lines next to the LV side of the transformer have a higher loading because all of the EC houses' demand flows through them before they are divided at different feeders to supply a portion of EC houses. Figure 8(a) displays the line loading of a line located at the beginning of the LVDN for the studied scenarios in one month. Figure 8(b) depicts the first four days of the month for greater clarity.

Scenario one resulted in a significantly higher line loading than scenario two. The line loading reached high values on weekdays and recorded lower loading on weekends. The

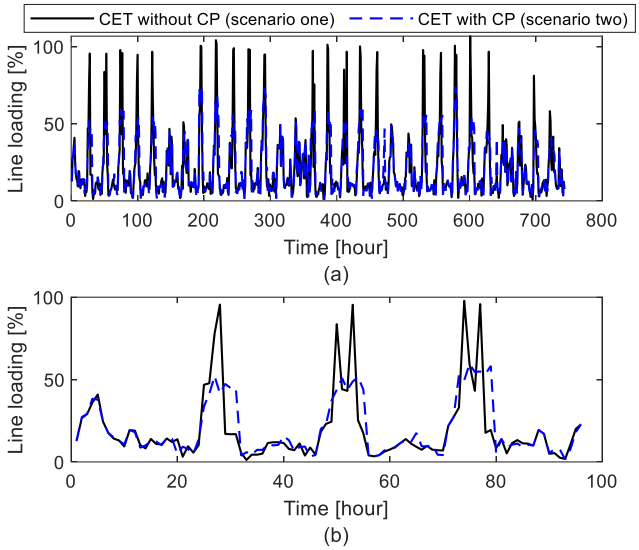

FIGURE 8. Loading of line. (a) one month, (b) four days.

reason is that the EC inflexible demand is lower on weekends than weekdays. Moreover, the retailer energy prices have small variations throughout the day hours on weekends compared to weekdays, which have large variations in retail prices throughout the day. Therefore, on weekends, there are no hours with simultaneous charging of almost all EC BES and EV, which happens on weekdays and causes the high peak demand. The line loading of scenario one surpassed the maximum loading limit and reached 106.76%, while scenario two recorded 74.15% maximum line loading, as given in Table 4. The proposed approach decreased the line loading by 30.55%. In scenario two, line loading decreased because of considering the contracted power cost in the EC objective function. The imports or exports from the retailer to the EC can not exceed the contracted power on that day. This

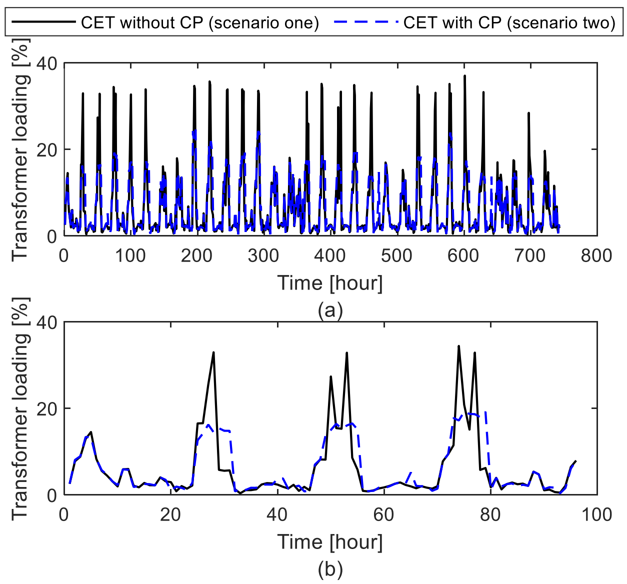

FIGURE 9. Loading of the transformer. (a) one month, (b) four days.

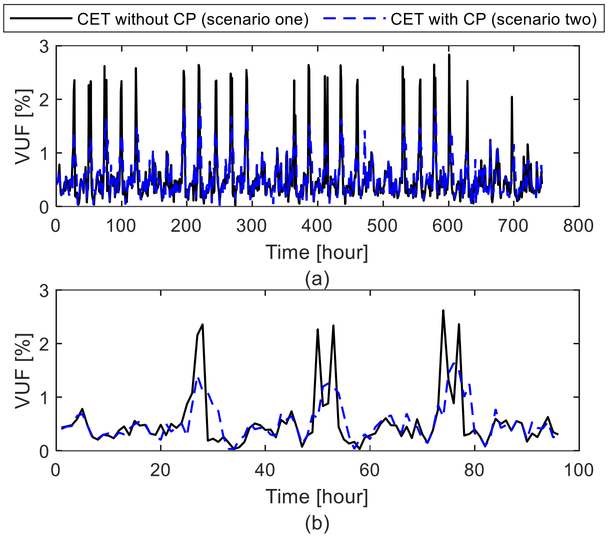

FIGURE 10. VUF (%). (a) one month, (b) four days.

demonstrates the ability of the proposed approach to reduce the impacts of CET on line loading.

Figure 9(a) displays the loading of the transformer for the studied scenarios in one month. Figure 9(b) depicts the first four days of the month for greater clarity. The loading of the transformer is low for both scenarios. However, scenario one resulted in a higher loading (i.e., 37.02%) than scenario two (i.e., 24.56%), as shown in Table 4. The proposed approach decreased the transformer loading by 33.66%. The loading of the transformer reached the highest values on weekdays and recorded lower loading on weekends, similar to the line loading. Due to the consideration of contracted power cost in the EC objective function in scenario two, the transformer loading dropped. The reason is that the energy exchanged with the retailer for the EC cannot go beyond the contracted power for that day. This proves the effectiveness of the proposed

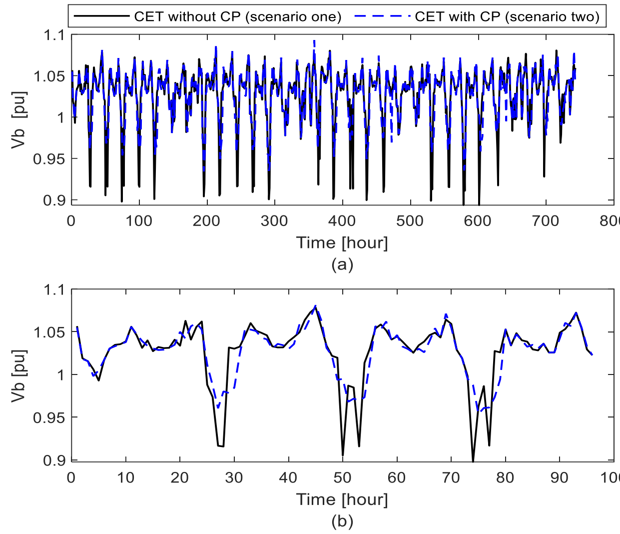

FIGURE 12. Voltage magnitude at phase b. (a) one month, (b) four days.

approach in minimizing the impacts of CET on transformer loading.

B. VOLTAGE UNBALANCE FACTOR

The voltage unbalance must be maintained within acceptable limits at distribution networks. The VUF% readings shown in Figure 10 have been collected at the node of house 53, which is positioned at the end of a long feeder, at which substantial voltage variations are predicted. As illustrated in Table 4 and Figure 10, scenario one resulted in a higher VUF than scenario two. The VUF of scenario one exceeded the acceptable limits and reached 2.84%, while scenario two recorded 1.93%, which is within acceptable limits. The proposed approach decreased the VUF by 32%. The VUF reached the highest values on weekdays and recorded lower values on weekends, similar to the line loading and transformer loading. This proves the effectiveness of the

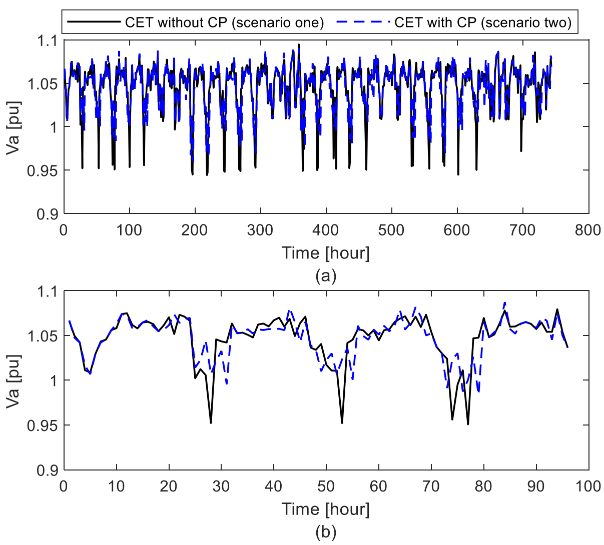

FIGURE 11. Voltage magnitude at phase a. (a) one month, (b) four days.

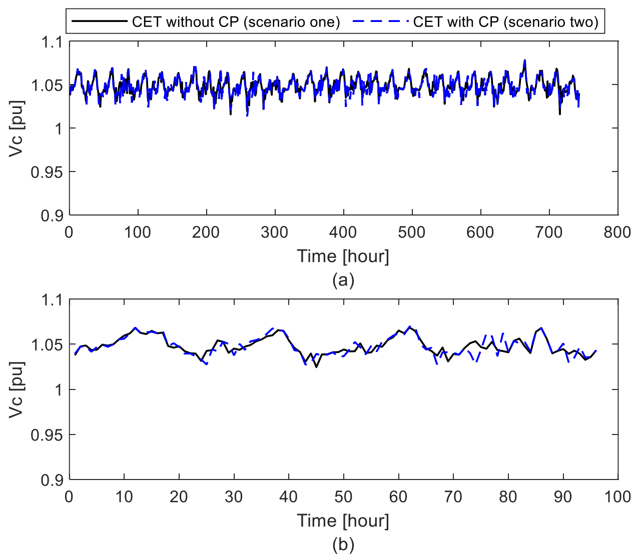

FIGURE 13. Voltage magnitude at phase c. (a) one month, (b) four days.

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proposed approach in minimizing the impacts of CET on voltage unbalance of LVDN.

C. VOLTAGE MAGNITUDES AT DIFFERENT PHASES

LVDNs are usually characterized by radial topology and lack voltage regulation devices. Therefore, keeping the voltage magnitude within limits is challenging, especially at the long feeders endpoints that are far from the transformer. Therefore, the voltage magnitude at house 53 for all phases is recorded. Many studies showed that the high penetration of DERs on LVDNs could increase the deviations in voltage [39]. Therefore, evaluating the voltage deviation under the CET context is important.

The LVDN under study is unbalanced, and the voltage magnitude of every phase is different. Therefore, the voltage magnitude of every phase is displayed in a separate figure. According to EN 50160 [40], the voltage magnitude maximum and minimum limits are 1.1 pu and 0.9 pu, respectively. Table 4 and Figure 11-Figure 13 illustrate that the voltage magnitude of different phases is within acceptable limits for both scenarios, except for phase b, which surpassed the lower limit and reached 0.893 pu in scenario one. The voltage variation of phase a and phase b is higher on weekdays than on weekends, similar to the line loading, transformer loading, and VUF. Moreover, scenario one shows more frequent large voltage deviations than scenario two, as shown in Figures 11(b) and 12(b).

D. SUMMARY OF IMPACTS OF CET ON LVDN CONSIDERING CONTRACTED POWER COSTS

The preceding subsections offered a thorough examination of the impacts of CET on LVDN for two scenarios. This subsection presents a statistical evaluation of the line loading, transformer loading, voltage unbalance, and voltage variations over one month. The discussed findings showed that scenario one caused violations in line loading, VUF, and voltage magnitude deviations, as well as higher transformer loading than scenario two. Moreover, the proposed approach in scenario two effectively eliminated these violations and decreased the maximum transformer loading recorded during the month. Figure 14 depicts a boxplot representation of CET impacts on the studied distribution network for scenario one and scenario two. The line loading of scenario one is usually below 60%, with outliers reaching 106.76%. The line loading of scenario two did not surpass 74.15%, with no outliers. The transformer loading of scenario one is usually below 20%, with outliers reaching 37.02%. The transformer loading of scenario two did not surpass 24.56%, with no outliers. The VUF of scenario one is usually below 1%, with outliers reaching 2.84%. The VUF of scenario two is usually below 1.3%, with outliers reaching 1.93%. The voltage magnitude of all phases is similar for both scenarios. However, in scenario one, phase a and phase b outliers reach lower values than in scenario two.

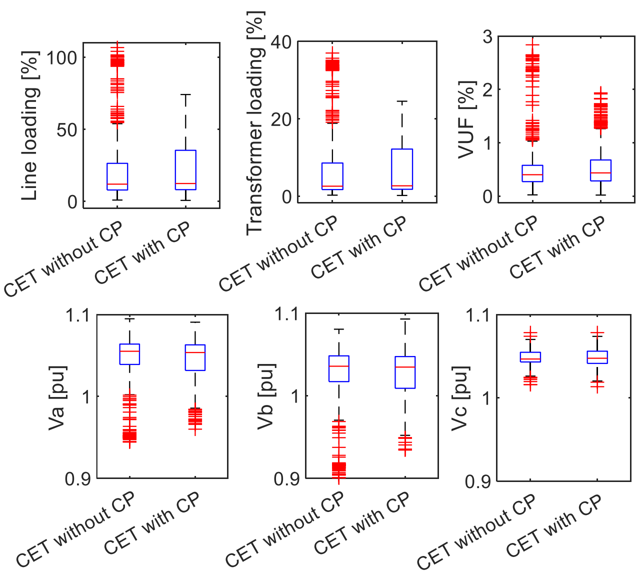

FIGURE 14. Boxplot representation of CET impacts on the studied distribution network.

V. CONCLUSION

Recent research studies have shown that when the low voltage distribution network (LVDN) limits are not considered, community energy trading (CET) can violate LVDNs limits. This study suggests integrating contracted power costs in the CET objective function in addition to energy cost to minimize the impacts of CET on LVDN. The suggested approach does not necessitate the inclusion of LVDN limits in the CET model, which reduces the computation complexity and avoids interactions with the distribution system operator. The results demonstrated that the suggested approach lowered the energy community's (EC) peak demand by 34.3% without impacting its economic performance, energy exchange with retailer, and the quantity of traded energy locally. Consequently, the suggested approach prevents LVDN limit violations in line loading, voltage unbalance, and voltage magnitude that occur in the CET scenario that does not take contracted power cost into account. The proposed approach decreased the line loading by 30.55%, the transformer loading by 33.66%, and the VUF by 32%. These factors are crucial for incentivizing the development of cost-reflective network tariffs, as tariff design can effectively address significant technical challenges in distribution networks.

APPENDIX

Variables	Description
$G_{t,h}$	Energy purchased from the retailer at instant t for house h
$I_{t,h}$	Imports (purchase) from other houses (i.e., peers) to house h at instant t
$E_{t,h}^{\mathrm{BES}}$	BES stored energy at time t and house h
$D_{t,h}^{\mathrm{BES}}$	BES discharge power at time t and house h
$D_{t,h}^{\mathrm{EV}}$	EV discharge power at time t and house h
$X_{t,h}$	Exports (selling) to other houses (i.e., peers) from house h at instant t
$E_{t,h}^{\mathrm{EV}}$	EV stored energy at time t and house h
$F_{t,h}$	Energy sold to the retailer at instant t from house h
$C_{t,h}^{\mathrm{BES}}$	BES charge power at time t and house h
$C_{t,h}^{\mathrm{EV}}$	EV charge power at time t and house h
$I_{t,h\leftarrow p}^{p}$	Energy imported (i.e., purchased) to house h from its peer p at instant t
$X_{t,h\rightarrow p}^{p}$	Energy exported (i.e., sold) from house h to its peer p at instant t
CP_{per}	Contracted power at period per
Parameters, scalars, and sets	**Description**
$dem_{t,h}$	Demand at time t and house h
$P_{t,h}^{PV}$	PV production at time t and house h
p_t^b	Purchase price at instant t
p_t^s	Selling price at instant t
p_{per}^{cp}	Contracted power cost for period per
η_C^{BES}	Efficiency of BES charging
η_D^{BES}	Efficiency of BES discharging
$P_{t,h,s}^{d}$	Net power demand at time t and house h
η_C^{EV}	Efficiency of EV charging
η_D^{EV}	Efficiency of EV discharging
$\bar{C}_{BES}$ and $\bar{D}_{BES}$	Upper bounds of BES charging and discharging powers
$\bar{C}_{EV}$ and $\bar{D}_{EV}$	Upper bounds of EV charging and discharging powers
$\underline{E}_{BES}$ and $\bar{E}_{BES}$	BES storage level lower and upper limits
$\underline{E}_{EV}$ and $\bar{E}_{EV}$	EV storage level lower and upper limits
b_t	Binary parameter value and time t. It indicates if the EV is connected to the charger or not.
p_{per}^{cp}	Contracted power price for period per
μ^{loss}	Loss factor due to P2P energy trade within EC
$t \in T$	Time instant t in time horizon T
$per \in P$	Period per in a set of periods P for contracted power
$h, p \in H$	House h and peers p in an EC of H Houses

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