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Voltage constraint-oriented management of low carbon technologies in a large-scale distribution network

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ABSTRACT

With the rising concerns about climate change and technological developments, the deployment of low carbon technologies (LCT) is gaining importance for reliable and sustainable power system operation. To decarbonize the heat and transportation sectors, LCTs such as heat pumps (HP) and electric vehicles (EV) are integrated into the power system from the low voltage (LV) distribution network, where predominantly end-users are connected. However, the increasing penetration of EVs and HPs, together with distributed photovoltaic (PV) systems on the demand side, can cause technical challenges in LV distribution networks, such as under/over voltages at the far end of the feeders. Therefore, the hosting capacity of a grid for LCTs is limited due to network constraints such as line ampacity, bus voltage, and frequency. In this paper, voltage-constrained management approaches for LCTs are proposed to improve the grid hosting capacity in a real large-scale distribution network. Moreover, HPs, PVs, battery energy storage systems (BESS), and EVs as well as their vehicle-to-grid (V2G) feature are evaluated as LCTs. The uncertain behavior of these technologies is taken into consideration for more realistic analyses. In addition, the charging and discharging interactions of BESSs are controlled by following the power consumption profiles from the economic point of view. Furthermore, the hourly carbon data is used to control BESSs from an emission-sensitive aspect. To demonstrate the effectiveness of the proposed algorithms, a series of tests is conducted on a real distribution network model. The results show that the hosting capacity of the considered LV network can be increased from 35% to 50% using the proposed algorithms. The promising results obtained in this study pave the way for future active LCT management studies to improve hosting capacity in urban networks, and pilot demonstrations in the field.

1. Introduction

1.1. Motivation and background

Decarbonization of the heat and transportation sectors has become one of the most significant aims of policymakers in recent years, as there is a huge interest in reducing carbon emissions and creating alternative sources to fossil fuels. Electric vehicles (EVs) and heat pumps (HPs) are considered promising potential solutions to achieve the net-zero carbon target. Despite recent global supply chain issues, 2 million EVs were sold worldwide in the first quarter of 2022, according to the Global EV Outlook 2022 by the International Energy Agency (2022). Moreover, the global market for HPs has grown remarkably, by around 4.6% annually between 2011 and 2021. This increase was realized as 28% for Germany in 2021, despite the issues with the production and delivery phases (REN21, 2022).

However, the electricity that is going to be used to charge EVs and supply power for HPs must be produced by renewable sources to make sense in terms of carbon targets and sustainability. Therefore, there has been a high demand for integrating residential photovoltaic (PV) systems in the last decade. However, integrating new power system players on both supply and demand sides in large numbers will require power system upgrades, particularly in low voltage (LV) distribution networks, with high investment costs. This will be challenging from an operational point of view (Andrianesis and Caramanis, 2020; Radi et al., 2022; Xie et al., 2022). Furthermore, not only the cost but also social and policy problems, such as insufficient experienced technical

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staff, public unwillingness, long approval times for projects, and poor communication between parties, can cause delays in the upgrading of power systems (Pall et al., 2016, 2019).

Therefore, operational management of these rapidly deployed low-carbon technologies (LCTs) has gained more importance to keep power system investments as low as possible in a sustainable power distribution context. Thanks to the communication infrastructure, grid flexibility can be enhanced, and the hosting capacity of distribution networks can be improved by controlling the LCTs (Yao et al., 2022). The ultimate aim of this study is to develop voltage-constrained management models to increase the hosting capacity of a real integrated medium voltage (MV) and LV network by mitigating technical challenges that arise from combinations of LCTs in LV distribution networks.

1.2. Literature review

There is a growing body of literature exploring the integration of different types of LCTs into power systems. However, these studies typically focus on the hosting capacity of one or two types of LCTs in a distribution network, neglecting the potential impacts of other emerging technologies.

Several studies have investigated the impacts of different LCTs on power system operation, including voltage profile, frequency, and power quality. Kazemtarghi et al. (2022) studied the impacts of bidirectional power flows due to vehicle-to-grid (V2G) operations of EVs on power systems, while Torquato et al. (2018) evaluated the hosting capacity of PVs in real LV systems. Ahmed et al. (2022) examined the impacts of battery energy storage systems (BESSs) and PVs on LV network operations, and Mulenga et al. (2021) focused on PV hosting capacity in distribution networks. Power and energy control methods were proposed for a microgrid in Parol et al. (2020), and Lamedica et al. (2022) proposed a power factor correction algorithm for fast EV charging stations. Spertino et al. (2022) aimed for optimal voltage control in LV networks with the aid of on-load tap changers and PV inverters, while Jayasekara et al. (2015) developed a multi-objective optimization problem to locate BESSs optimally in distribution networks. Contreras et al. (2022) developed an interaction quota method to maintain the possible congestion and grid use in an optimal way. Delfino et al. (2019) presented an energy management model enabling control of active and reactive powers in MV/LV microgrids. However, some of these studies did not consider all LCTs, such as HPs, EVs with/without V2G, and residential PVs, BESSs, and EVs with/without V2G, or did not test their proposed models in large-scale MV/LV networks with residential customers.

In the field of energy management in microgrids and distribution networks, several studies have proposed various strategies for utilizing distributed energy resources. Lundberg et al. (2022) aimed to control voltage in a decentralized manner during overvoltage periods caused by high penetration of distributed energy resources. However, EVs, HPs, and BESSs were not considered together, and the method was not tested in an MV/LV network. Pippi et al. (2022) investigated a method to overcome under/overvoltage challenges in MV/LV distribution networks using the reactive power of renewable energy resources and the active power of BESSs. However, the study did not include EVs and HPs, and tests were conducted in a test network instead of a real MV/LV network. Maulik (2022) proposed a power management strategy for a grid-connected microgrid that considered EVs and BESSs but neglected HPs and the V2G option of EVs. Erenoğlu et al. (2022) presented an energy management strategy that minimized losses in a microgrid, including wind and PV farms, EVs, and BESSs, but did not include the V2G feature of EVs and HPs, and the study was conducted on a five-node test system. Arias et al. (2022) presented a hierarchical optimization model to manage EVs' charging demand, taking users' satisfaction into account, but did not consider HPs, PVs, BESSs, and carbon impacts, despite testing on an MV/LV network. Edmunds et al. (2021) assessed the hosting capacity increase in various LV networks and took into consideration EVs with V2G, PVs, and HPs, but ignored BESSs as an LCT type.

In addition, the literature on energy transition is growing, offering valuable insights into achieving sustainable energy through policies, stakeholders, and systems. The works in Falcone et al. (2018, 2019) explored instrument mixes and networking dynamics in the Italian biofuel industry for the sustainable energy transition. Additionally, in a recent study, the authors explored the perspectives of regional stakeholders towards the Gela and Porto Marghera biorefineries in Italy to transition towards bioenergy (Falcone et al., 2021). Besides, Magazzino and Falcone (2022) assessed the relationship between waste generation, wealth, and GHG emissions in Switzerland, and propose policy measures for optimizing municipal solid waste in a circular economy perspective. Furthermore, a number of recent studies have explored effective approaches for reducing carbon intensity and achieving a low-carbon transition in heavy industry. The authors in Xu and Xu (2022b) used a semiparametric econometric approach to identify an effective way of reducing carbon intensity in heavy industry. Similarly, Xu et al. (2021) used a semiparametric regression model to explore the driving forces of distributed energy resources in China. Xu and Chen examined how to achieve a low-carbon transition in heavy industry from a nonlinear perspective (Xu and Chen, 2021). The work in Xu and Xu (2022a) assessed the role of environmental regulations in improving energy efficiency and reducing CO2 emissions in the logistics industry. These studies provided important insights for policymakers and industry stakeholders seeking to transition towards sustainable energy systems.

None of the studies reviewed in this literature examined all of the LCTs, which include EVs with V2G, HPs, PVs, and BESSs, in a comprehensive manner, either in a residential or central context. Additionally, the carbon emission impacts of these emerging technologies, which are a critical factor in their deployment, were not investigated in most of the analyzed studies, except for (Delfino et al., 2019). However, even in that study, the V2G option for EVs and a large and real distribution network were not included in the testing.

1.3. Contributions and paper organization

This study propounds various management strategies for residential LCTs in a large-scale MV/LV distribution network to figure out possible under voltage issues due to the high penetration of LCTs. The ultimate aim of the proposed models is to increase the penetration level of LCTs and to reduce energy-related carbon emissions in the daily operation of the distribution network. The investigated distribution network belongs to the Irish power system operated by ESB Networks. It is worth highlighting that the considered system and its modeling process were introduced in detail in the previous study by the authors (Mehigan et al., 2022).

The main contributions of this study are threefold:

1. To the best knowledge of the authors, this is the first study that proposes voltage-oriented management of LCTs including HP, PV, BESS, and EVs with V2G feature together to improve the grid capability for the mentioned LCTs.
2. To benefit from the rooftop PVs more effectively, the charging/discharging interactions of BESSs are coordinated considering the power consumption profile of the households. Moreover, this approach ends up increasing the capability of the network for the considered LCTs.
3. To highlight the applicability of the CO_2 emission-oriented power system operation, the hourly CO_2 emission data in Ireland are utilized for decisions on the charging and discharging interactions of BESSs.

The remainder of the study is organized as follows. The used methodology and the proposed algorithms are detailed in Section 2. Section 3 exhibits the case studies together with the input data, and the test results. Finally, concluding remarks are highlighted in Section 4.

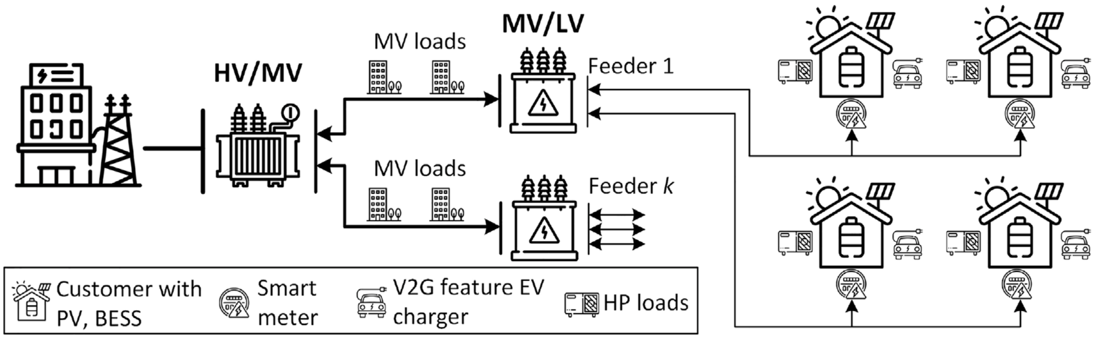

Fig. 1. The demonstration of the distribution network and considered LCTs.

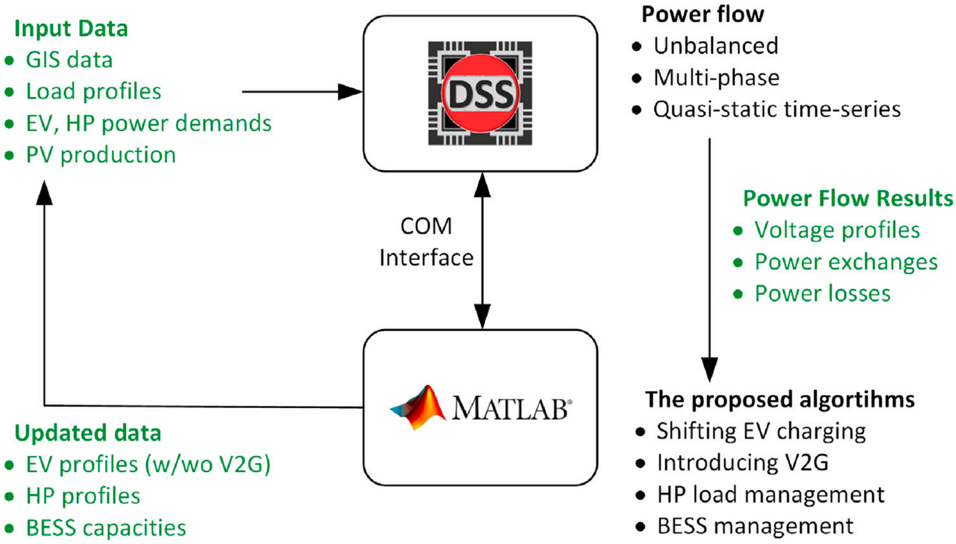

Fig. 2. The overview of OpenDSS-MATLAB com interface simulation.

2. Methodology

A demonstration of an example MV/LV network model to be controlled by the proposed algorithms is given in Fig. 1. As seen in the figure, each residential customer is assumed to own behind-the-meter EV, HP, PV, and BESS as LCT along with a smart meter located at their point of common coupling. It is worthy of note that only the LV sides of the network are focused on while controlling the LCTs due to the lack of data for the other parts of the MV network.

Fig. 2 shows the overview of the co-simulation process used throughout the study. While EPRI's Open Distribution System Simulator (OpenDSS) (Dugan and Montenegro, 2022), which is an open-source power system analysis tool, is used for the power flow analysis, thanks to the COM interface ability, the proposed algorithms are implemented via MATLAB. OpenDSS is capable of performing unbalanced, multi-phase power flow with both snapshot and time-series options. In this work, quasi-static time series (QSTS) simulations are conducted to enable capturing of time-varying and time-independent occurrences for daily simulations. As can be deduced from Fig. 2, the network model, load profiles, and LCT power profiles are the initial data set to be given in OpenDSS. At the end of the power flow, voltage profiles, power exchanges, and losses are obtained and transferred to MATLAB via the COM interface. By introducing the proposed algorithms in MATLAB, EVs' charging demand can be shifted and the V2G feature can be activated, also HPs' power consumption can be interrupted and BESS can be managed by considering residential load profiles and carbon intensity data. After that, the updated data is replaced with the previous data as input to OpenDSS for the next power flow run.

The proposed EV charging control method can be seen in Algorithm 1. Firstly, a daily power flow simulation is run with the initial data of EV charging demand, HP power profile, and PV power production. After that, the power flow results are obtained such as customers' voltage profiles, total power consumptions, reactive power flows, power losses, etc. By using the gathered data, the problematic buses are determined by checking if the voltage profile is between 1.1 pu and 0.9 pu, and the information regarding the bus numbers and the related time periods are stored. After determining the buses, whether an EV is plugged in or not at that bus is checked, if yes, the charging demand of the EV is shifted later than the first time period when the voltage level is seen above the level of 0.9 pu. If there is no EV plugged in at the determined bus, the closest bus fed by the same LV network is checked if another EV is charging at that moment. Then, the same shifting process is applied to that EV being charged considering the voltage level of the bus. Finally, the evaluated EVs' charging profiles are updated and stored for the following power flow run. Moreover, the used algorithm for controlling the HP load is given in Algorithm 2. As can be deduced from the algorithm flow, a similar procedure to the EV charging control algorithm is followed to manage the HP loads of the applicable households. The only difference is that the power consumption of the related HP is stopped for the time periods being determined in case of a low voltage level in a bus.

Additionally, the V2G feature of EVs is taken into consideration to cope with the low voltage issues still being encountered after shifting EV charging. Algorithm 3 presents how V2G from the EVs is taken advantage of. It should be underlined that EVs' battery degradation is not considered and an assumption was made that EV owners agreed

Algorithm 1 EV charging control

```
RUN daily power flow in OpenDSS
obtain voltage, power results from OpenDSS
if $V_{bus_{i,t}} < 0.9$ then
    $V_{event_{i,t}}$ = store the related bus numbers and the time periods
end if
for $i = 1$ to length($V_{event_{i,t}}$) do
    if an EV is plugged in at the related bus and time periods then
        stop charging the related EV and shift it later than the first time period when $V_{bus_{i,t}} > 0.9$
    else
        check if an EV is plugged at the next bus fed from the same LV
        if yes then
            stop charging the related EV and shift it later than the first time period when $V_{bus_{i,t}} > 0.9$
        end if
    end if
end for
update parameters
RUN daily power flow with the updated parameters
```

Algorithm 2 HP operation control

```
RUN daily power flow in OpenDSS
obtain voltage, power results from OpenDSS
if $V_{bus_{i,t}} < 0.9$ then
    $V_{event_{i,t}}$ = store the related bus numbers and the time periods
end if
for $i = 1$ to length($V_{event_{i,t}}$) do
    if an HP is in operation at the related bus and time periods then
        stop working of the HP up until the first time period when $V_{bus_{i,t}} > 0.9$
    else
        check if an HP is in operation at the next bus fed from the same LV
        if yes then
            stop working of the HP up until the first time period when $V_{bus_{i,t}} > 0.9$
        end if
    end if
end for
update parameters
RUN daily power flow with the updated parameters
```

Algorithm 3 EV charging control with V2G

```
RUN daily power flow in OpenDSS
obtain voltage, power results from OpenDSS
if $V_{bus_{i,t}} < 0.9$ then
    $V_{event_{i,t}}$ = store the related bus numbers and the time periods
end if
for $i = 1$ to length($V_{event_{i,t}}$) do
    if an EV is plugged in at the related bus and time periods then
        stop charging the related EV and shift it later than the first time period when $V_{bus_{i,t}} > 0.9$
    else
        check if an EV is plugged at the next bus fed from the same LV
        if yes then
            stop charging the related EV and shift it later than the first time period when $V_{bus_{i,t}} > 0.9$
        end if
    end if
end for
update parameters
RUN daily power flow with the updated parameters
obtain voltage, power results from OpenDSS
if $V_{bus_{i,t}} < 0.9$ then
    $V_{event_{i,t}}$ = store the related bus numbers and the time periods
end if
for $i = 1$ to length($V_{event_{i,t}}$) do
    if an EV is plugged in at the next bus fed from the same LV then
        Start discharging of the EV until the first time period when $V_{bus_{i,t}} > 0.9$
    end if
end for
reupdate parameters
re-RUN daily power flow with the updated parameters
```

to participate in the V2G program. In the first part of this algorithm, a similar shifting of the EV charging process to Algorithm 1 is conducted. Following the shifting process, the next power flow analysis is run with the updated parameters. The new voltage profiles are rechecked whether or not they are within the allowed limits, if not, the V2G algorithm is introduced. To do this, the availability of a charging EV at the next bus fed by the same LV network is examined, if so, the EV is discharged for the time periods of low voltage occurrence at the relevant bus. It should be underlined that the discharging power rate of EVs can be determined before the analysis is performed.

Last but not the least, the customers on the LV networks are capable of having BESSs together with rooftop PV units on their premises. In addition, the charging and discharging decisions of the BESSs can be made by considering two different approaches. While firstly, the BESSs are controlled by considering the consumption profiles to make the most of PV production in an economic manner, the hourly CO_2 emission data are utilized to operate the system much more sensitive to the carbon targets in the latter approach. In the first approach, the power consumption profiles of the residential customers in the LV network are used to create generalized decision-making profiles during the day for BESSs. By considering the profile, the BESSs are discharged while the peak load periods and charged during the non-peak hours. Moreover, the power consumption related to EVs and HPs along with the power produced by PVs are taken into account while creating the profile. By doing so, the benefits of using BESSs are aimed to be enhanced in terms of both economical and technical aspects. On the other hand, for the second approach, daily CO_2 emission data for Ireland are collected to determine the daily carbon intensity profile. After that, charging and discharging CO_2 levels are determined to trigger BESSs for the relevant actions to be taken. If the daily carbon data is above/below the discharging/charging trigger level, the BESSs are discharged/charged until either their capacity is satisfied or CO_2 emission level is reached the triggers' level. In the next step, the amount of prevented emission is calculated by using the hourly carbon intensity data. Thanks to the proposed method, it would be shown that a power system could be operated in particular by BESSs with a less carbon footprint during the peak-carbon periods and by storing energy coming from renewable-based generation, decreasing the carbon emission is possible.

3. Case study

In this study, a real large-scale MV/LV distribution network operated by the Irish DSO ESB Networks is considered throughout the investigation. Fig. 3 reflects the focused MV/LV distribution network. It is worth mentioning that the considered network is operated with a 10 kV MV feeder with 2188 customers in total. It should be stated that the evaluated network consists of mainly residential customers together with a less number of industrial or commercial premises. In addition

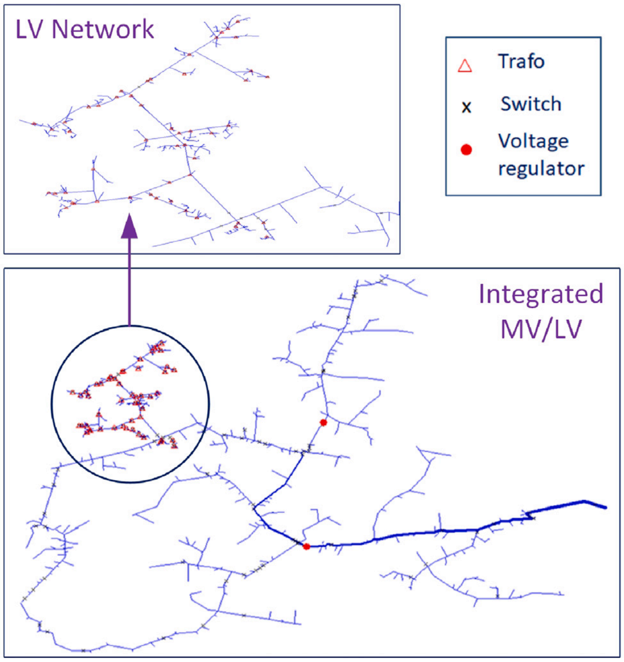

Fig. 3. The detailed topology of the considered MV/LV distribution network.

to the MV feeder, 51 real LV networks are integrated, containing 317 customers, where 12 of them are 3-phase. While the modeling of the MV side is realized by considering directly connected loads which is representing the other 1871 clients, LV sides are modeled thoroughly by considering each individual customer's load and its types. Further information and the modeling process of the considered network can be found in the authors' previous work (Mehigan et al., 2022).

3.1. Input data

In this paper, the load profiles allocated for MV and LV customers are obtained from the CREST Demand Model (Richardson et al., 2010) which is an open-source tool to generate realistic load profiles considering the number of occupants, the types of home appliances, etc. The aggregated load demands for both MV and LV networks in the pilot field are shown in Fig. 4.

As for the EV behaviors, the actual arrival, departure times, and charging duration times data are collected from the region where the modeled LV network belongs within the project conducted by the Irish DSO company ESB Networks (ESB Networks, 2021). Fig. 5 demonstrates the statistics related to EV owners' behaviors. As seen from the figure, EVs are generally plugged in after 8 pm. Moreover, the ending times for charging processes are mainly seen being between 2 am and 5 am. However, EVs start to depart after 8 am and it lasts until 11 am which proves that EV charging demand can be shifted without violating the EV owners' comfort. Similarly, the real HP data from ESB Networks' project is used to generate HP load demands for the end-users in the LV network. The generated HP load profiles for the considered penetration levels are seen in Fig. 6. Also, the rooftop PV units are taken into consideration as renewable-based power sources in this study. As for the PV integration, although the micro-generator capacity allowance is 6 kW for residential customers in Ireland (ESB Networks, 2022), it is thought that each household can have a 2.1 kWp PV panel. So that, the rest of the capacity is reserved for other micro-generator types such as energy storage, EVs with V2G. Fig. 7 demonstrates the aggregated daily output power of PVs on the LV part of the network with respect to different penetration levels.

Regarding the BESSs allocation, it is assumed that each household that has the rooftop PV unit can have a 7.5 kWh BESS in the relevant case. While the charging/discharging rate of the BESSs is 2 kW, the state-the-charge (SoC) level for the deep charging is 20% (sonnen, 2022). The CO_2 emission data that are used for the BESS control are obtained from Ireland's TSO company EirGrid (EirGrid Group, 2022). 20 consecutive work days data are collected to demonstrate the daily CO_2 emission in Ireland as seen in Fig. 8.

3.2. Results

To assess the efficacy of the proposed algorithms, a series of simulations with varying combinations of LCTs and management models are conducted. It should be noted that while the evaluated LCTs are only available for low voltage (LV) networks' occupants, the load demands are included for both LV and MV customers. By increasing the penetration levels of LCTs, the voltage levels for the LV network transformers are monitored, and the hosting capacity of the large-scale network is determined. Through the incremental integration of LCTs, it is concluded that without any management algorithm, at most 35% of LV customers can use electric vehicles (EV), heat pumps (HP), and photovoltaic (PV) systems in an MV/LV integrated network. Fig. 9 displays the voltage statistics for a daily simulation of the MV/LV network before and after the introduction of LCTs. It is observed that when the penetration level reaches 35% for LCTs, the voltage levels exceed the limit of 0.9 pu in some of the transformers in the LV network. It should be emphasized that battery energy storage systems (BESSs) and any management algorithm for LCTs are not incorporated in this case.

After the hosting capacity of the network is determined, the penetration level of LCTs is increased to 40%. The voltage changes of each LV transformer are analyzed and the results are presented in Fig. 10, where the yellow boxes represent the case without any management of LCTs and the purple ones stand for the case including EV charging and HP operation management algorithms. It is evident that the proposed algorithm successfully maintains the voltage levels above the limit of 0.9 pu. However, the evaluation does not include the V2G feature of EVs and BESS. It is noteworthy that 41 out of 111 EVs' charging demands (36% of the EV owners) are shifted, and 21 out of 111 HPs' operations (18% of the residents) are stopped for short time periods to keep the voltage level within the limit. Fig. 11 illustrates the changes in the aggregated EV charging demand in the LV network with and without EV management. Furthermore, it is seen that EVs' charging demands are mostly shifted to between 3 am and 11 am which means that EV owners' departure times are not violated seriously. In addition, those who are not satisfied with the new departured time can unplugged their EVs before the relevant time.

Subsequently, the LV/MV network is assessed by increasing the penetration of LCTs to 45%. The voltage profile changes during the day for different cases are depicted in Fig. 12. The impact of the increased penetration level on the voltage profile is investigated by comparing the yellow boxes, representing the case with 40% penetration and no management algorithm, and the green boxes, which represent the case with 45% penetration without any management of LCTs. As expected, the voltage violation rate has increased. To mitigate this challenge, EVs with V2G capabilities are integrated, and the proposed algorithm is implemented. The purple boxes in the same figure illustrate the maintained voltage levels for each LV transformer due to the V2G algorithm. It is noteworthy that 43 out of 116 EVs' charging profiles are modified by the shifting and V2G algorithm, whereas only 4 out of 116 HPs' operations are interrupted in this case.

The study also includes an analysis of the impact of residential BESSs on the flexibility of the power system. To evaluate this, the penetration levels of existing LCTs are increased by 5%, and households

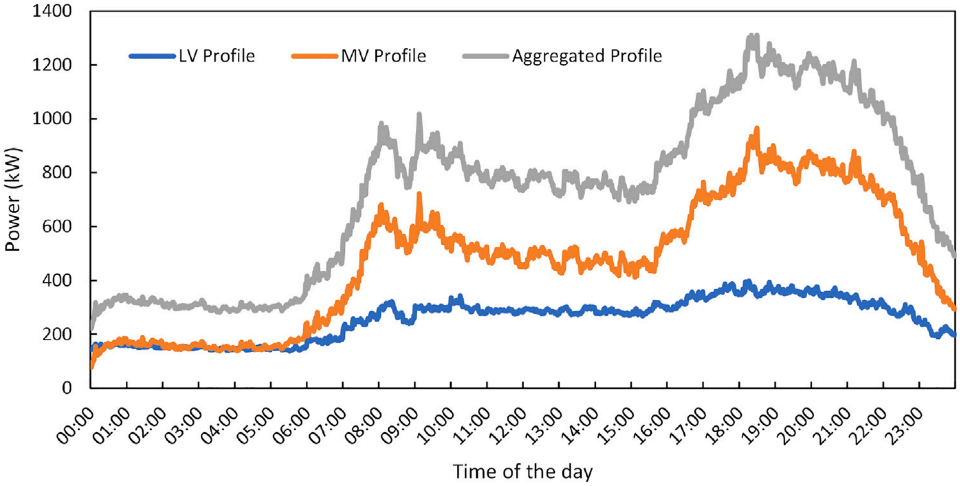

Fig. 4. 24 h base load profile for MV, LV and combined MV and LV demand.

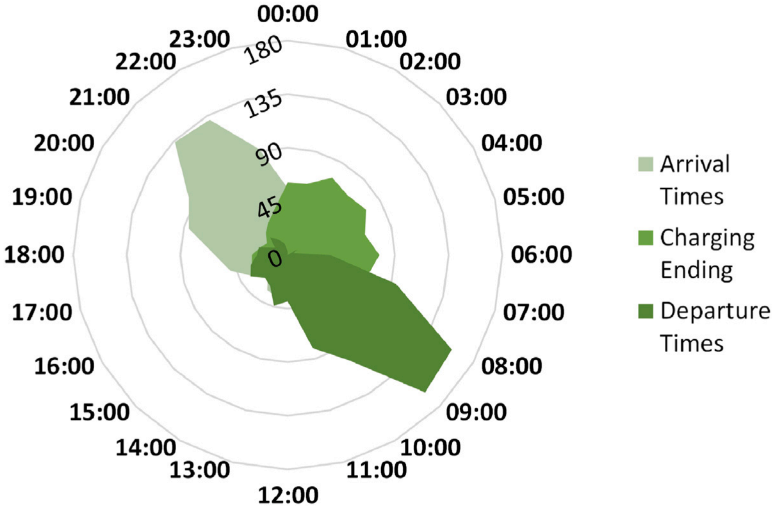

Fig. 5. The number of EVs together with their arrival, charging, and departure times.

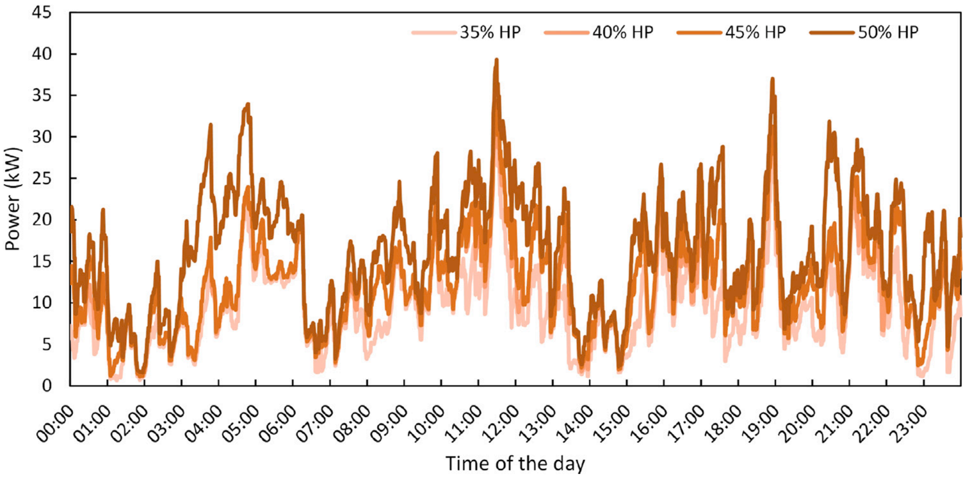

Fig. 6. 24 h base load profile for MV, LV and combined MV and LV demand.

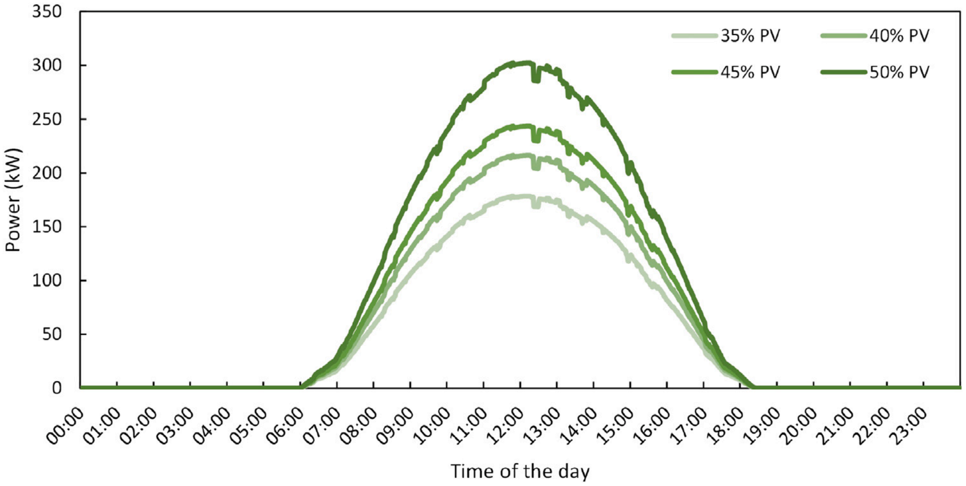

Fig. 7. 24 h base load profile for MV, LV and combined MV and LV demand.

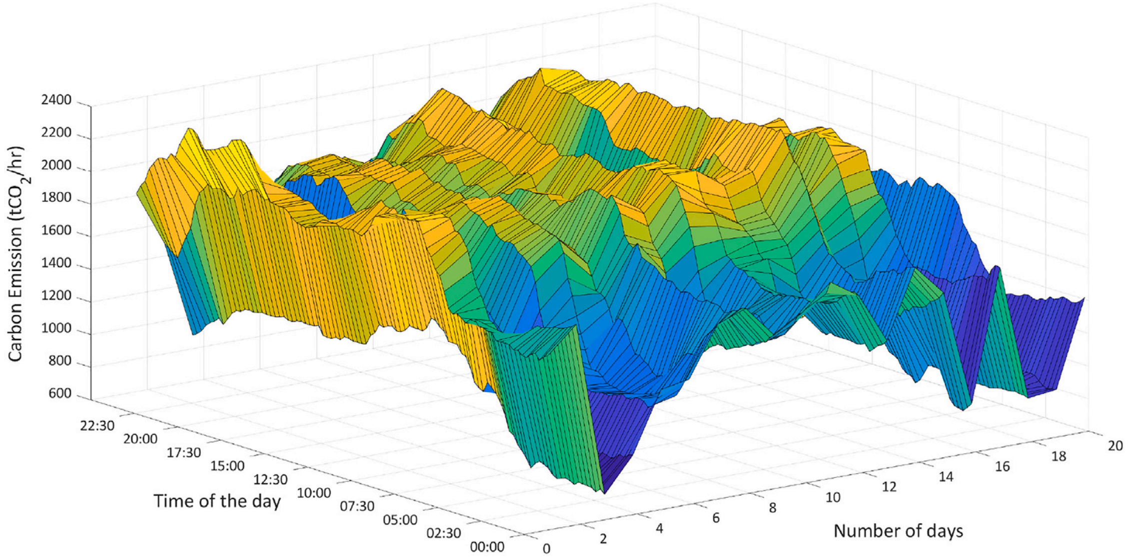

Fig. 8. The considered hourly CO_2 emission data used throughout the study.

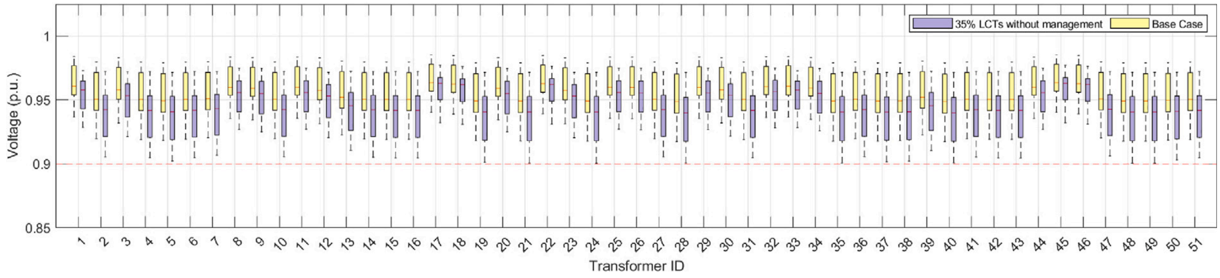

Fig. 9. The voltage variations for LV transformers with/without LCTs.

with PV units are equipped with a 7.5 kWh capacity BESS. The negative effects of increasing penetration levels are shown in Fig. 13, where the yellow and green boxes are compared. The proposed algorithm for LCTs is then incorporated to ensure that the voltage levels remain above the limit. Additionally, the charging and discharging interactions of the BESSs are managed by considering the generalized daily load profile of end-users to optimize their economic benefits. The results indicate that while 32% of EV owners' charging patterns are changed, only 10% of HP operations are halted for less than ten minutes.

To show the effects of using different control parameters for BESS on the distribution system operation, the load following and carbon following modes are compared in this work. The main objective of using load follow mode is to improve the advantage taken by incorporating PVs and BESS. On the other hand, the decarbonizing of the power system has gained increased attention in recent years. The carbon following mode involves controlling the BESSs based on the hourly CO_2 intensity data of Ireland. The voltage level comparisons of the two scenarios are shown in Fig. 14, with the management of LCTs deactivated to observe

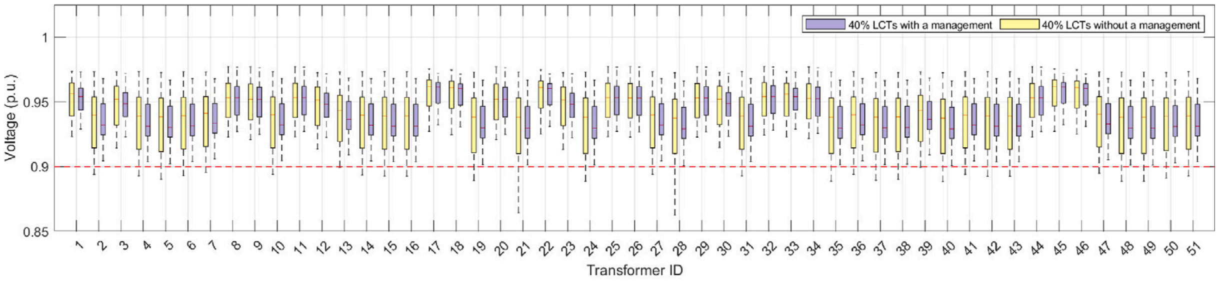

Fig. 10. The voltage variations of LV transformers before/after introducing EV charging management with 40% LCT penetration.

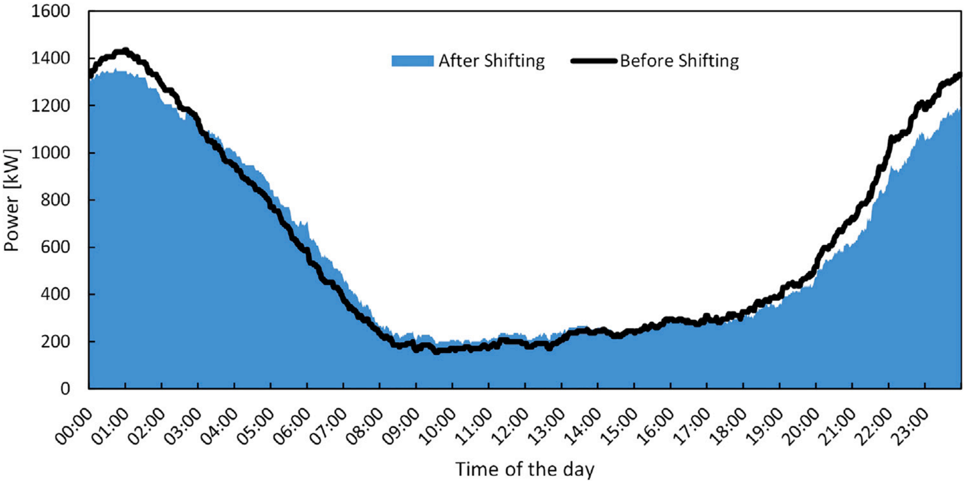

Fig. 11. The aggregated power profile of EV charging before/after shifting process.

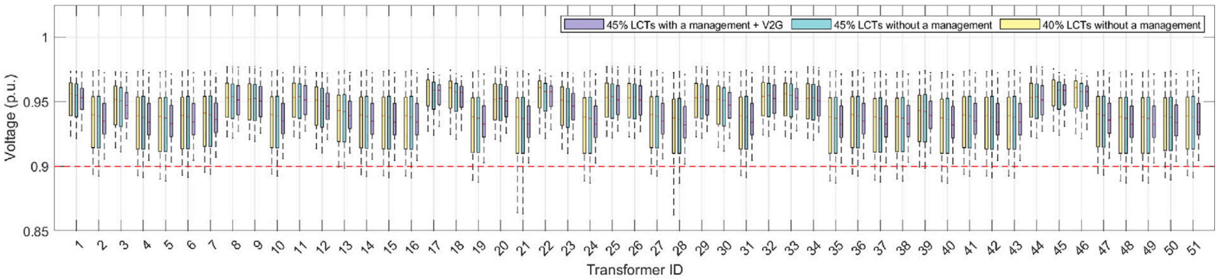

Fig. 12. The voltage levels for LV transformers with and without LCTs after introducing V2G feature of EVs.

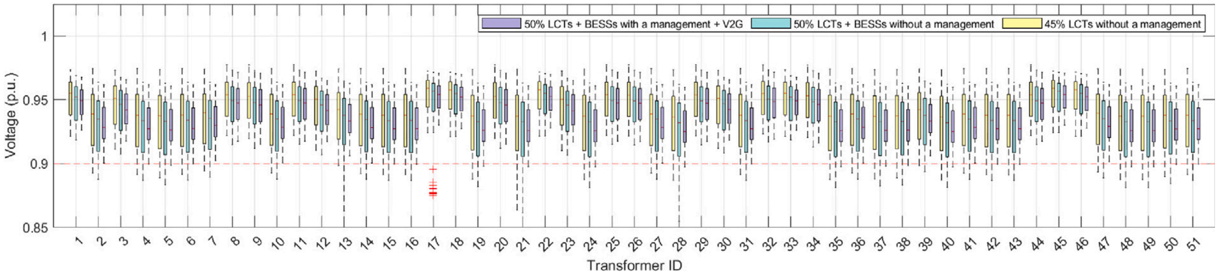

Fig. 13. The voltage levels for LV transformers with and without LCTs.

the impacts directly. The results indicate that the control of BESSs with the carbon following mode negatively affects voltage levels. While the proposed algorithm can maintain voltage levels within limits, doing so could significantly decrease end-users' satisfaction as margins for some LV transformers are much higher compared to load following modes. Furthermore, Fig. 15 presents the SoC level of one BESS to verify the effectiveness of the carbon-based control mechanism. Herein, the hourly carbon intensity data for the relevant day is represented by the dark blue continuous line, while the dashed green and the dotted red lines indicate the charging and discharging trigger carbon levels for the BESS. When the carbon data falls below the green dashed line, the BESSs are charged, and when the carbon data exceeds the

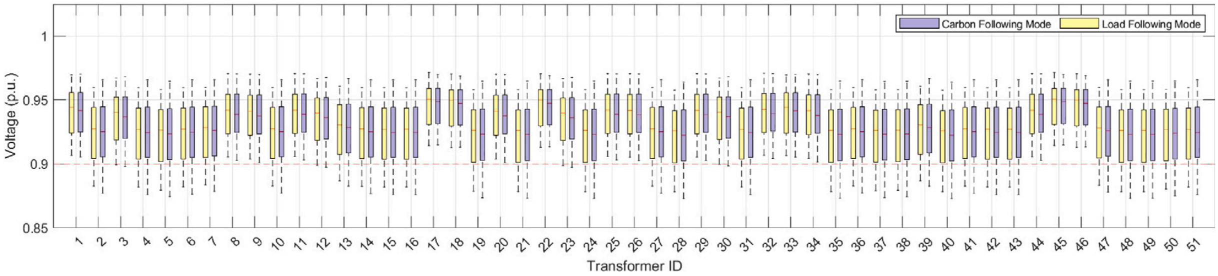

Fig. 14. The voltage levels for LV transformers Carbon and Load dispatch mode.

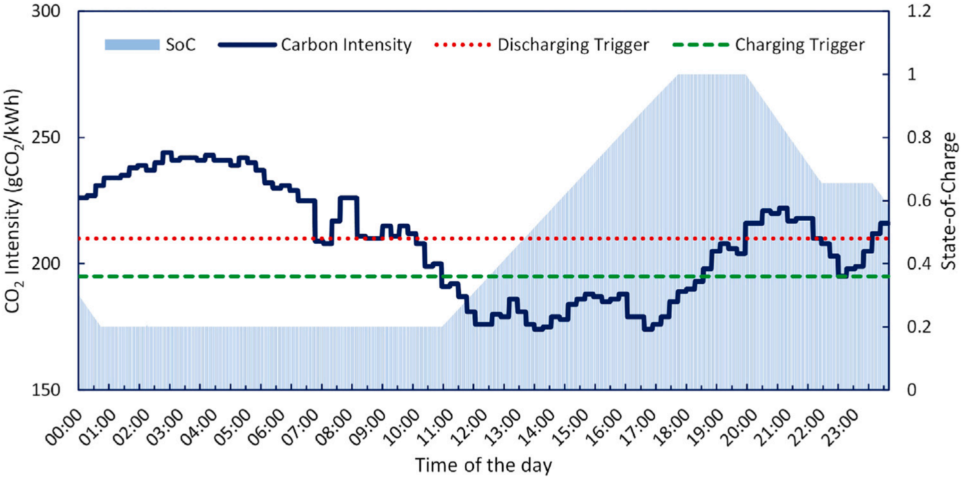

Fig. 15. The SoC of BESS Changes.

determined above level (green dashed line), the energy stored in the BESSs is consumed to prevent much carbon emission. The light blue bars show the SoC level of the BESS, which increases in the charging mode below the green dashed line or decreases in the discharging mode above the dotted red line, as expected. Furthermore, Fig. 16 depicts a comparison of carbon emissions between load and carbon following modes for the considered network. To evaluate the impact of the initial State of Charge (SoC) level of BESSs on carbon emissions, simulations are carried out at two different SoC levels, namely 30% and 60%. In both cases, the carbon following mode control of BESSs enables the shifting of carbon emissions to less carbon-intensive periods of the day. As expected, a higher reduction in carbon emissions is achieved when the initial SoC level of BESS is 60% because the carbon intensity is high and above the discharging trigger level of BESS in the early morning of the day. In the cases of 30% and 60% initial SoC levels, the reductions in CO$_2$ emissions are 0.35% and 0.88%, respectively. However, it should be noted that only 50% of the LV customers have BESS, and MV customers are not considered in these cases, indicating that there is considerable potential for emission reduction in the entire power system. Additionally, it is worth mentioning that the emission impacts of LCTs are beyond the scope of the study.

4. Conclusion

This study presented various voltage constraint-oriented management algorithms for LCTs such as EVs, HPs, PVs, and BESSs in an integrated large-scale and existing MV/LV distribution network in Ireland. Firstly, the hosting capacity of the LV part of the considered network was determined for the evaluated LCTs as 35% of customers in the relevant region. Following this, the proposed algorithms were activated in order as the penetration level increased to maintain the voltage violations. In the case of 40% penetration level, the voltage levels were kept within the limit of 0.9 pu only by managing 36% of EVs' charging demand and 18% of HPs' operation. By taking advantage of EVs' V2G option, this penetration level could be increased to 45% level; besides, it was achieved by manipulating 37% of EVs and only 3% of HPs. When it comes to 50% penetration level, BESSs were deployed in the residents and the caused voltage violation was removed by managing only 32% of the EVs and 10% of the HPs. It should be highlighted that the BESSs are controled by considering LV customers' power consumption profile to get the most out of PV production from an economical point of view.

In line with the carbon targets, the impact of the use of CO$_2$ intensity data for controlling the BESS on the distribution network operation was investigated which was the contribution that distinguished this work from the existing studies in the literature. To show the impact of the initial SoC level of BESSs, two different initial SoC levels were considered which were 30% and 60%. It was deduced from the study, the control of the electricity grid is possible in a carbon emission-oriented way. Thanks to the proposed following mode, carbon emission was decreased by 0.35% and 0.88% in the cases of 30% and 60%, respectively for a daily operation. Also, it is worth underlining that only 141 residential customers in the LV network were assumed to have BESS with 7.5 kWh capacity in this study. It was deduced from the results that the number of customers having BESS, the capacity and initial SoC levels of BESSs play the leading roles in decreasing carbon emission levels in daily operations. Also, it should be reminded that carbon reductions due to use of LCTs were not included in this study. On the other hand, considering only the carbon emission-focused methods might cause technical challenges to keep the network stable and sustainable. To overcome these challenges, the deployment of LCTs needs to be increased and controlled effectively in a technical context.

In summary, expanding LCTs in the power system is crucial for achieving carbon emission reduction targets. However, there are some limits on the expansion of LCTs that need to be considered. One of the major limitations is the intermittent nature of renewable energy sources

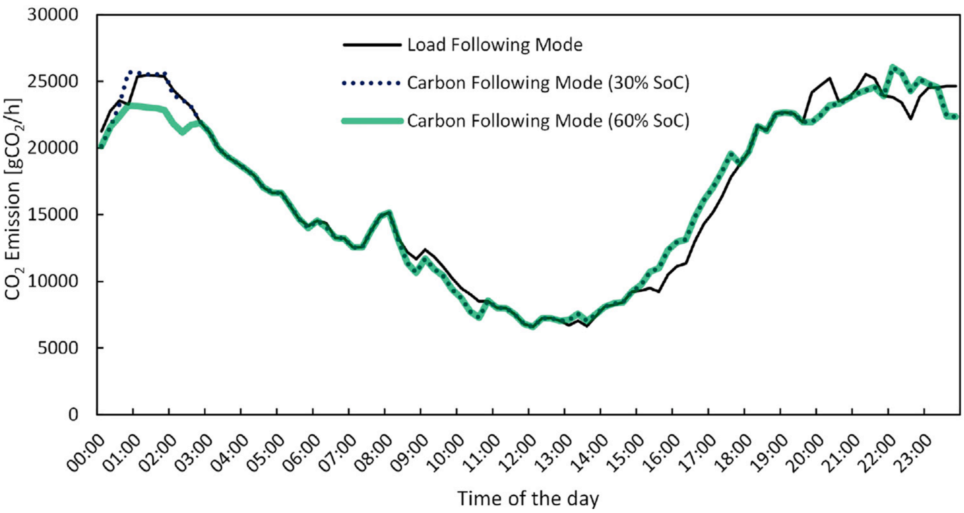

Fig. 16. The carbon emission comparison of load and carbon following modes.

such as solar and wind power, which can cause voltage and frequency stability issues. Moreover, the integration of LCTs into the existing power system may require significant upgrades in transmission and distribution infrastructure, which can be costly and time-consuming. In addition, the variability of LCTs' generation can lead to overloading and congestion in the power system. The intermittency of LCTs also makes it difficult to match the supply and demand of electricity, which can result in the need for energy storage solutions such as batteries. Finally, the current policy and regulatory frameworks may not be sufficient to incentivize the deployment of LCTs, which can hinder their expansion in the power system. Therefore, it is essential to address these limits and develop appropriate strategies to integrate LCTs into the power system effectively. This study revealed that the penetration level of LCTs could be significantly improved by managing LCTs and creating effective synergies among them. However, further expansion requires upgrading the infrastructure, and regulating the relevant policy accordingly. It is worth noting that the economic and financial aspects of LCTs and their applications are beyond the scope of this study, and further research is needed to evaluate the economic feasibility of LCTs and to propose improvements regarding carbon sequestration and diversion from fossil fuels. The study's promising results pave the way for future studies on active LCT management aimed at improving the hosting capacity of urban networks. These findings also set the stage for pilot demonstrations in the field.

It is important to mention that while the physics of power systems are well studied, it is a challenge to assess the stochastic nature of LCTs. This study used (Richardson et al., 2010) to handle the uncertain behavior of loads, PV, and other LCT's in power systems. Our model utilizes a Monte Carlo simulation technique to find optimal system configuration and operation strategies that perform well under a variety of future conditions. Note additionally that the studied variables can have an unknown form of interaction that might not be captured by our model. Future work opportunities include incorporating interactive effects into our model like the factor model proposed in Bai (2009).

As a future extension of this work, the power system constraints together with carbon following operations of BESS can be evaluated in an optimization problem framework in order for fewer impacts of carbon following mode on the technical challenges in power system operation.

CRediT authorship contribution statement

Ibrahim Sengor: Software, Investigation, Writing – original draft. **Laura Mehigan:** Methodology, Investigation, Data curation. **Mustafa Alparslan Zehir:** Methodology, Conceptualization, Resources, Writing – review & editing. **Juan J. Cuenca:** Conceptualization, Resources, Writing – review & editing. **Ciaran Geaney:** Validation, Formal analysis, Writing – review & editing. **Barry P. Hayes:** Supervision, Formal analysis, Writing – review & editing.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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