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Published in:
Journal of Energy Storage

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
Link to publication record in Queen's University Belfast Research Portal

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Impact of the deployment of solar photovoltaic and electrical vehicle on the low voltage unbalanced networks and the role of battery energy storage systems

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Abstract

Keywords: Electric vehicles, Solar PV, Unbalanced LV networks, Battery energy storage systems, Low Carbon Technologies

The deployment of low carbon technologies (LCTs) such as solar photovoltaics (PVs) and electric vehicles (EVs) is increasing due to their various benefits. However, their rapid integration in the residential networks imposes critical technical issues to the network operators. In this paper, a sensitivity analysis is conducted to investigate the impact of these technologies on low voltage unbalanced residential networks located in Northern Ireland. Different penetrations are investigated, and the results are assessed using various technical indices. The simulations are performed using actual load measurements in a 10-minute resolution obtained from the network operator of Northern Ireland. The impact of LCTs on the phase imbalance is considered by analyzing the voltage unbalance and neutral losses. The results suggest that monitoring each feeder and phase separately and consider the voltage unbalance in the assessment as it can be violated without a voltage magnitude violation occurring, in addition, the farthest nodes from the transformer bus were found to be very sensitive to violations. The solution-based community battery energy storage systems (BESS) is investigated by introducing sizing and scheduling algorithms to solve the network issues and enhance the network performance using black-box optimization. The results proved the wide capability of the community BESS in providing the network with different services. The main purpose of this study is to provide a full understanding of the future challenges posed by the deployment of LCTs and the role of BESS in accelerating the transition towards a low carbon future by supporting the network operation.

1 Introduction

Distribution system operators (DSOs) are facing major challenges arising from the rapid deployment of low carbon technologies (LCTs) on the low voltage residential network (LVNR). The two main contributing technologies are solar photovoltaics (PVs) and electric vehicles (EVs). Their deployment is increasing rapidly due to their economic and environmental benefits, in addition to the vast decrease in their cost and the maturity level they have reached. In the UK and Northern Ireland, the integration of LCTs is increasing to fulfil the zero-emission target by 2050 [1]. This commitment has forced several regulations to be introduced in order to encourage customers to own these technologies by offering subsidies, including tax deduction, feed-in tariff and microgeneration export programs [2].

The impact of LCTs is widespread as they can affect different network levels. The main issue with the LVNR is the lack of measurement devices and monitoring. In Northern Ireland, there is as of yet no policy decision for smart meter rollout, which contributes to the lack of visibility of the LV network. Hence, it is very difficult for the DSO to take the proper actions at the right time to avoid curtailing power delivery. Furthermore, regulations are enforced by the ESQCR to protect the network security and power quality such as the G98 connection recommendation that limits the PV feed-in power for single-phase connections to 3.68 kW [3], which restrict prosumers to export their excess generation and hence it is considered as wasted energy. The technical challenges behind the use of LCTs are voltage violations beyond the allowable limits, thermal overloading on the transformers and cables, and high power losses in both phase lines and neutral. Severe voltage unbalance (VU) can also occur due to the rapid deployment of these unmanaged technologies.

There are different conventional and smart solutions that can be applied to maintain the safe operation of the LVNR. Battery energy storage systems (BESS) have been considered recently as a powerful option due to their different environmental, economic, and technical benefits, especially their crucial role in facilitating the safe integration of more LCTs to support the energy evolution towards low carbon future. The BESS can be utilized to achieve different technical goals and solve various challenges in the LVNR. In the LVNR, the BESS can be installed along the feeders, at the transformer bus, or at the properties behind the meter. According to current regulations, DSOs cannot operate, manage, or own energy storages [4]. Hence, DSOs aim to utilize the storage units owned by third parties and individuals to provide the network with the needed support in return for agreed payments.

In Northern Ireland, the DSO (NIE Networks) is facing some network challenges due to the rapid deployment of LCTs at the low voltage level. These challenges affect the power stability, quality, and security of different network levels. Hence, NIE Networks is investigating different conventional and innovative smart solutions to mitigate these challenges. One of these solutions is the Facilitation of Energy Storage Services (FESS) project [5]. This project will provide a framework to integrate third-party customers/aggregators energy storage systems (ESS) to enhance the performance of Northern Ireland distribution networks.

The aim of this paper is to analyze the impact of LCTs on Northern Ireland LVNRs as well as investigating the role of community BESS in mitigating the LCTs challenges.
a) Literature Review

In the literature, there are many studies investigating the impact of LCTs on LVRNs. In [6], probabilistic assessments using Monte Carlo simulations are conducted for different LVRNs located in the UK to evaluate the impact of LCTs on the network constraints. The results showed that 50% of the tested networks faced some violations in node voltages or thermal ratings. In [7], the impact of EV charging on the LVRN is assessed for a network located in Ireland. The study showed that with 20-40% penetration of EV, the network limitations will be violated. However, both studies have not considered the phase VU factor rate in the analysis based on specific standards. The phase VU rate (PVUR) defined by IEEE [8] was considered in [9], where the LCTs impacts are assessed in terms of energy losses and voltage problems. However, the definition of PVUR is not accurate enough and may lead to inexact results as it does not consider the line voltage and the phase angle. Furthermore, the study [9] did not consider the impact of LCTs on thermal overloads of the feeders and transformer.

The impact of high PV penetration on the LVRN in the UK was studied in [10]. The study concluded that the LVRN safe PV penetration limit is around 75%. However, the study focused only on the impact of PV on the network voltage and did not consider the thermal overloading and the unbalanced nature of the LVRN. The impact of EV charging on LVRN located in Budapest is addressed in [11], where the voltage stability and transformer loading were only considered. The impact of EV on LVRN located in the UK is presented in [12]. The study employed deterministic and probabilistic approaches, and the results revealed that the violations occurred to node voltages and main feeder with 33% EV penetration, while the distribution transformer was found to be overloaded for all the EV uptake scenarios. However, the VU was not considered which is a crucial factor that should be considered in evaluating the impact of LCTs. The EV charging drawbacks on LVRN located in Malaysia are analyzed in [13], the results showed that the LVRN can accommodate up to 10% of EV without exceeding the network constraints.

The impact of LCTs on the LVRN varies from one network to another as it depends on the location, type, and specifications of the network. Additionally, the regulations and standards define the network constraints, thus, affecting the network hosting capacity. As a consequence, there are differences in the results in the literature related to this topic. Furthermore, the assessment methodology applied in addition to the adopted assumptions also affect the results. When analyzing the impact of LCTs, it is important to consider three-phase unbalanced power flow calculations and define properly the technical indices used in the assessment. In addition, the LVRN headroom should not be defined by a specific value unless the network has only one feeder. For the LVRN with multiple feeders, the hosting capacity should be determined for each feeder independently besides the transformer headroom.

The integration of BESS to support the LVRN against the LCTs challenges has proved to be an attractive option as demonstrated by recent projects and reported in the literature. As a part of low carbon network fund projects in the UK, Scottish and Southern Electricity Networks has investigated the application of small-scale BESS (25 kWh / 25 kW) in assisting the LVRN operation and performance [14]. The project deployed three single-phase units of the same size at street level and utilized the BESS inverter active and reactive power in peak shaving, and voltage regulation as well as improving the phase imbalance and power quality. The BESS proved its capability in regulating the voltage by ±7 V and reducing the network peak by a maximum of 100 Amps over the day in addition to improving the network power quality.

The use of BESS for peak shaving in the LVRN has been addressed in [15], where a probabilistic method was adopted to assess the capability of behind the meter BESS in peak shaving. The study considered the impact of residential PV and heat pumps. The size of community BESS at LVRN was determined to solve the voltage and feeder largest problems in [16] using rule-based approach. While the BESS was controlled using linearized optimal power flow (OPF) to maintain the voltage and line flow within the acceptable limits. Yet, the previous studies modelled the LVRN as balanced network and ignored the LVRN unbalanced nature. The phase balancing using BESS was addressed in [17], where the capability of BESS in optimizing the VU was proved in addition to enhancing the operation of the LVRN. The study investigated different locations for the BESS, and the results suggest that the BESS should be installed at the feeder’s end node.

In [18], an approach is introduced to allocate, size and dispatch behind the meter BESS optimally on the LVRN. Mixed-integer linear programming was employed for the BESS allocation, while linear programming was used to settle the BESS active and reactive power dispatch through three-phase OPF by linearizing the constraints to minimize the total cost of system installation as well as managing the violations. Yet, the study did not consider the phase imbalance in their analysis. Another residential BESS control approach based on multi-objective optimization using particle swarm has been introduced in [19] to optimize the VU, voltage deviation, power losses and PV curtailment. The formulation adopted OPF using penalty factors to consider the network and BESS constraints. However, the BESS sizing based on the LCTs potential impacts has not considered. In addition, the previous studies considered only the impact of PV and did not consider other evolving LCTs such as the EVs.

The community BESS sizing and sitting in unbalanced LV networks was introduced in [20] to minimize the BESS installation costs as well as maintaining the network constraints within the allowable limits. The study considered the network constraints represented in node voltages, VU, and line flows which were formulated as hard constraints in the OPF problem. However, OPF is NP-hard problem due to the nonconvexity associated with the equations and constraints which may result in convergence to a local point of infeasibility [21], hence, other methods should be considered in formulating the nonlinear constraints to reduce the complexity through linearization, convex relaxation, or by using soft constraints [22]. The BESS control to mitigate VU in the LVRN has been addressed in [23]. However, the study did not consider other network constraints such as node voltage and line flow.
Few studies have addressed the integration of BESS in Northern Ireland distribution networks. In [24], an investigation of system services that can be delivered by the BESS has been addressed through a case study on an actual distribution network located in Northern Ireland. The study investigated the active/reactive power capability of the BESS in supporting the network operation and performance. In [25], BESS allocation, sizing, and scheduling approach is introduced for congestion management, the study investigated different installation scenarios to solve the anticipated high LCTs uptake in Northern Ireland. The look-ahead scheduling and real-time operation of BESS to provide the distribution networks of Northern Ireland with many ancillary services including grid power levelling, reactive power support, power quality improvements have been addressed in [26], [27]. Another study in [28] addressed the integration of BESS in Northern Ireland distribution networks to maximize self-consumption of wind energy and maximize the returned BESS revenues. However, none of these studies addressed the impact of LCTs or the integration of BESS on the LVRN of Northern Ireland.

b) Contributions

This paper complements the previous studies by providing an assessment methodology to analyze the impact of LCTs in the LVRN as well as investigating the sizing and scheduling of a community BESS to solve the LCTs challenges and enhance the network performance and operation. The main contributions of the paper are as follows:

1) Investigating the impact of LCTs on LVNRNs located in Northern Ireland. Unlike the studies mentioned in the literature review that focus on specific indices or specific technology, the proposed assessment methodology covers most of the network technical indices as well as studying the impact of PV and EV on the network in addition to considering the unbalanced nature of LVRN to provide a complete picture on the LCTs impacts and the network hosting capacity. Three LVRN located in Northern Ireland are adopted and the assessment include observing the VU, phase voltage, feeder and transformer loadings, phase line losses, and neutral losses.

2) Introducing a sizing algorithm for the community BESS to overcome the potential congestion caused by the future penetrations of LCTs. The objective of this sizing algorithm is to find the minimal BESS size to reduce the investment cost that solves network violations represented in node voltage violations, VU, and feeder’s overloads.

3) Proposing a look-ahead scheduling algorithm for the community BESS that aim to optimize the VU and reduce the energy losses in neutral and phases as well as maintaining the LVRN technical constraints within the acceptable limits.

4) Evaluating the proposed BESS sizing and scheduling algorithms on an actual LVRN located in Northern Ireland with the LCTs uptake scenario of 2030. In addition, the impact of the BESS scheduling algorithm on the BESS degradation is evaluated using a semi-empirical Li-ion ageing model.

It is worth mentioning that the assessment methodology introduced in this paper considers analyzing the impact of LCTs on the neutral losses. Furthermore, the proposed scheduling and sizing algorithms are introduced for three-phase community BESS which considers the complexity of three-phase model and network in addition to formulating the OPF problem as a black-box optimization and modelling the constraints in the objective function as a feasibility problem, which reduces the complexity of the formulation as well as the computation time. Moreover, the proposed BESS scheduling algorithm aims to reduce the neutral losses as one of its objectives. To the best of authors’ knowledge, these aspects have not been addressed previously in the literature.

The paper is organized as follows: Section 2 presents the modelling of networks and LCTs, Section 3 presents the impact assessment methodology, the impact assessment results are given in Section 4, the BESS model, sizing, and scheduling algorithms are presented in Section 5, the BESS case study and simulation results are given in Section 6, finally the conclusion is given in Section 7.

2 LCTs Assessment Modelling

In this section, the models used in this paper are explained which are related to the test networks, EV charging profiles, PV generation profiles, and the future LCTs uptake scenario of 2030 for Northern Ireland.

a) LVRN Models

Three test LVRN are being used to evaluate the impact of LCTs on the network constraints. These networks are located in Northern Ireland, UK and connected to the 11 kV network through 11 kV / 400 V transformers with different ratings. The transformers do not have on-load tap changing capability and the sending voltage at the transformer bus is set at +3.75% of nominal (i.e., 415 V). Each transformer feeds a number of households through underground three-phase/four-wire feeders of different sizes. Details on the number of households and feeders for each network are given in Table 1. The feeders are labelled as units (i.e., from U2 to U6 for LVRN_1), the simplified schematics for the test LVNRNs are given in Figure 1.

<table>
<thead>
<tr>
<th>Network ID</th>
<th>Number of Households</th>
<th>Number of Feeders/units</th>
<th>Feeders’ labels</th>
<th>Transformer rating [kVA]</th>
<th>Typical day max demand [kVA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVRN_1</td>
<td>92</td>
<td>5</td>
<td>U2 – U6</td>
<td>250</td>
<td>66.77</td>
</tr>
<tr>
<td>LVRN_2</td>
<td>95</td>
<td>4</td>
<td>U3 – U6</td>
<td>300</td>
<td>72.59</td>
</tr>
<tr>
<td>LVRN_3</td>
<td>103</td>
<td>4</td>
<td>U3 – U6</td>
<td>350</td>
<td>73.11</td>
</tr>
</tbody>
</table>

Table 1. Test LVNRNs details

The network details and aggregated measurements are provided by the DSO of Northern Ireland (NIE Networks). As mentioned in the introduction, there is a lack of monitoring devices on LV networks in Northern Ireland, hence, three-phase measurements for a specific period in August 2019 for each feeder of each LVRN were only provided by the DSO in 10-minute resolution. To illustrate an example of these measurements, the transformer power of LVRN_1 for the 23rd of August 2019 is illustrated in Figure 2.
b) EV Modelling

The EV charging is random as it depends on people’s behaviour. Hence, probabilistic methods are being used to generate different patterns. Three parameters should be defined to generate the EV charging patterns: 1) start time; 2) EV battery state of charge (SoC), and 3) charging power.

1) **Start time:** the start time of the EV charging cycle can be arbitrarily assigned. However, to mimic the real starting time, one-year data of actual residential EV charging measurements obtained from the dataset of the Low Carbon London (LCL) project by UK Power Networks [29] was used. For each day, the first hour (cycle start time $T_s$) of the EV charging cycle is obtained. Afterwards, the daily values for one year are treated as a normal distribution function with ($\mu = 12.9478$, $\sigma = 8.4437$) and the cumulative distribution function (CDF) can be then illustrated in Figure 3, calculated as:

$$ F(T_s | \mu, \sigma) = \frac{1}{2} + \frac{1}{2} \text{erf} \left[ \frac{T_s - \mu}{\sqrt{2} \sigma} \right] $$  \hspace{1cm} (1)

Where $\mu$ is the mean, and $\sigma$ is the standard deviation. From Figure 3, various start times of EV charging cycles can be obtained randomly conditioned by this CDF.

2) **EV battery SoC:** the end time of the EV charging cycle can be determined using the battery SoC and the charging power. The EV battery SoC can be simulated as a CDF of the daily travel distance assuming that the daily travel distance of an EV is identical to the conventional vehicle as done in previous studies [30], [31]. The daily travel distances of conventional vehicles can be obtained from national surveys such as [32]. In this paper, the EV battery SoC model utilizes the same approach, where the lognormal is used to define the daily travel distance probability using the UK daily travel data from [32] with ($\mu = 3.2125$, $\sigma = 0.6537$), sequentially, the EV battery SoC as a CDF of the daily travel distance can be shown in Figure 4, calculated as:

$$ F(\text{SoC} | \mu, \sigma) = \frac{1}{2} + \frac{1}{2} \text{erf} \left[ \frac{\ln(1 - \text{SoC}) + \ln(dr) - \mu}{\sqrt{2} \sigma} \right] $$  \hspace{1cm} (2)

Where $dr$ is the maximum range of the EV. The $dr$ is taken as 150 km as an average value according to the EV battery. In this work, an average EV battery size of 45 kWh is adopted based on the popular EV available in the market [33]. By obtaining the EV battery SoC, the residual capacity to be charged for an EV charging cycle can be identified. More details on the EV battery SoC modelling can be found in [30].
3) Charging power: the charging power is determined according to the available residential EV chargers. Typical single-phase residential EV chargers’ ratings vary from 3 kW (slow/standard) to 7 kW (fast) [33]–[35].

After determining the start time, and the residual EV battery capacity to be charged, the end time can be settled according to the charging power. For specific EV charger rating, several EV charging patterns can be randomly generated conditioned to the CDF in Figure 3 and Figure 4 which were obtained using real data.

c) PV Modelling

The PV generation pattern depends mainly on the weather condition. In order to generate PV patterns, three parameters need to be settled; 1) start time; 2) end time; 3) generated power. The start and end times can be settled based on the geographical location, and season. While the generated power is affected by many factors like irradiance, clouds movement and module status (module efficiency, quality, and cleanliness). Different models can be applied to generate generation patterns of residential PV [36]. In this work, real measurements are obtained from [37] for two PV sizes, 4 kWp and 6.5 kWp due to their popularity in Northern Ireland and the UK. It should be noted that for the impact assessment and BESS sizing case study, ideal PV generation are adopted to simulate the worst-case scenario [38], while for the BESS scheduling case study, actual PV measurements are used adopted from [37].

d) 2030 Scenario

The deployment of renewable generation and LCTs is expected to increase massively in Northern Ireland by 2030 [39], [40] due to the net-zero carbon target. In this paper, the anticipated penetrations of EVs and PVs are determined based on 2030 projections to analyze the impact of these penetrations on the LVNRNs. Projections by the transmission system operator (SONI) suggest that the number of electric vehicles in Northern Ireland may reach 250,000 by 2030 [39]. According to the Northern Ireland Statistics & Research Agency, the population in Northern Ireland will reach 1.95 million by 2030 [40]. The average size of a household in Northern Ireland is 2.5 ~ 3 persons on average [41]. Thus, 0.4 EV/household is projected in Northern Ireland by 2030. According to the available data on the Zap-map for the residential chargers in Northern Ireland [42], the deployment percentage of each EV charger (3 kW and 7 kW) is 50%, hence 0.2 EV/household for each charger rating is projected by 2030. For PV deployment, according to recent data provided by NIE Networks, the number of PV with microgeneration connection represents 3% of the households in Northern Ireland. According to future projections by the national grid, the number of solar rooftop PV will represent 20% of the houses by 2030 [43].

3 LCTs Impact Assessment Methodology

In this paper, the proposed methodology in assessing the impact of LCTs is divided into two parts; the first part is to simulate different penetration scenarios assuming that the LCT penetration is divided equally across the three phases, the second part is to simulate the LCTs penetration on a single-phase to assess their impact on the voltage unbalance. The following indices are recorded to analyze the impact properly.

- Feeder Voltage: For the EV assessment, the minimum phase voltage in the day is recorded as per-unit, while for the PV, the maximum voltage is recorded. The phase voltage allowable limits in this work are taken as 230V +10% / -6% (216.2V – 253V) in agreement with the UK ESQCR [44].
- Cable Loading: Maximum line flow in the day for each feeder is considered as a percentage of maximum current carrying capacity.
- TransformerLoading: Maximum transformer loading in the day is recorded.
- Daily Line Losses: The total daily loss in energy of each feeder is considered in each case.

For the unbalanced assessment, in addition to the previous indices, the following two indices are also considered:

- Voltage Unbalance (VU): VU is a factor representing the voltage deviation of each line voltage to the average line voltage. In this work, the approximated factor [45] of the true definition of voltage unbalance [46] is adopted. The approximated factor is adopted to ease the process of determination as it does not require the negative sequence components and to avoid the use of complex algebra while providing more accurate results compared to the IEEE PVUR [45], expressed as:

\[
VU_{tu} = \frac{(v_{uh} - v_{uh})^2 + (v_{uc} - v_{uc})^2 + (v_{ub} - v_{ub})^2}{v_{uh}^2}
\]

(3)

\[
VU_{av} = \frac{v_{ub} + v_{uc} + v_{uh}}{3}
\]

(4)

Where the subscripts \(u\) represents the unit/feeder, \(t\) is the time index, and the superscript \(av\) denotes average voltage, and the other superscripts are related to line-to-line voltage. In the UK, the maximum allowable limit of VU is considered as 2% according to the Engineering Recommendation P29 [47].

- Daily Neutral Losses: The daily energy loss in the neutral of each feeder is considered in each case.

The previous indices are determined by performing time-series power flow calculations. In this work, the backward/forward

Figure 4. CDF of EV battery SoC

Figure 3.
method for three-phase unbalanced power flow calculation [48], [49] is used due to its effectiveness in the calculations and convergence for the unbalanced LVRN. The adopted algorithm is validated using the power system software (NEPLAN) [50].

In this paper, a deterministic approach is applied to assess the LCTs impact on the LVRN by applying various penetrations of LCTs on the network using typical day load measurements. The worst-case scenario is concerned, hence for the EV start time, it is assumed that all the EVs are starting to charge at the same time (18:00 hr). The probability of this is currently very low, however, in the carbon-free future when the majority of vehicles are EVs, this case will likely be normal. For the PV, ideal PV generation profiles for the UK in August are adopted for the two adopted PV sizes [38].

4 LCTs Impact Assessment Results

To evaluate the LCTs impact on the LVRNs, detailed analysis are provided for the first network (LVRN_1) as it has more feeders compared to the other two networks, while the results summary for the other two networks are given.

a) Balanced Distribution

The LCTs penetration is distributed equally on the three phases. The simulations are conducted for various penetrations of PVs / EVs as a percentage of households, for the first network (LVRN_1), the LCTs distributions are as follows: a) 20 EVs / PVs = 21.7% of the households, b) 40 EVs / PVs = 43.4% of the households, c) 60 EVs / PVs = 65.2% of the households, and d) 80 EVs / PVs = 86.9% of the households. The simulations are conducted for 50% EVs of 3 kW, 50% EVs of 7 kW, 50% PVs of 4 kWp and 50% PVs of 6.5 kWp. The number of the LCTs/unit for each case is distributed according to the number of households in each unit as given in Table 2 for the first network (LVRN_1). The results of the LCTs impact assessment for different penetrations of LCTs are shown in Figure 5 – Figure 7.

Table 2. Number of EVs/PVs per unit for each case (LVRN_1)

<table>
<thead>
<tr>
<th>Number of LCTs</th>
<th>Total</th>
<th>U2</th>
<th>U3</th>
<th>U4</th>
<th>U5</th>
<th>U6</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>40</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>60</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>80</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>24</td>
<td>8</td>
</tr>
</tbody>
</table>

Figure 5. Feeder voltage for different number of LCTs (LVRN_1)

Figure 6. Maximum cable loading for different number of LCTs: (a) PVs, (b) EVs

Figure 7. Maximum transformer loading for different number of LCTs

As shown in Figure 5 – Figure 7, the high penetrations of EVs and PVs will lead to severe violations. These figures show the violated units only. It can be noticed that the farthest nodes from the transformer bus (U5) had the most severe violations in terms of voltage. Furthermore, the impact of EVs on cables overloading for both the transformer and cables is higher than the impact of the PVs, while, the PVs have a higher impact on the feeder overvoltage. The violations occur mainly after 43.4% of LCTs uptake. Below this percentage, cable overloading occurred only for Phase B of U2. This is because Phase B of U2 is already heavily loaded by normal demand. Regarding the network losses, the LVRN with high penetration of PVs will...
have a higher energy loss compared to the EVs. This is because PVs generate power during long periods in the summer. Moreover, for higher LCTs penetrations, the losses tend to increase exponentially. The total network daily loss in energy for different cases is given in Table 3.

As shown in Figure 8, the LCT hosting capacity varies from one feeder to another in each network according to the feeders’ parameters. These values represent the maximum allowable LCT hosting capacity before network violation occurs (voltage violation and cable overloads). Note that, the previous analysis was conducted for the worst-case scenario, where all the EVs are assumed to start charging at the same time, while ideal PV generation profiles were used. Additionally, typical demand measurements were used. However, for other assumptions, these values may be subject to change. It can be concluded that the LCTs impact on low voltage networks differs according to the network specifications (i.e., feeder parameters, transformers, number of households in each feeder) as well as the analysis assumptions. Hence, for each feeder in a network, an impact assessment should be conducted with regard to the DSO’s data and assumptions.

b) Unbalanced Distribution

In this part, another sensitivity analysis is conducted to estimate the impact of LCTs with varying penetration on the phase imbalance. The impacts of this variation are examined for two units of the first network (LVRN_1) selected based on the feeders’ lengths with respect to the transformer bus; the nearest (U2) and the farthest (U5). For each unit, the LCTs penetration is varied for only one phase (Phase A) which represents the worst-case scenario. It is assumed that the number of households of each unit is divided equally on the three phases (6 houses/phase for U2 and 10 houses/phase for U5). The simulations are conducted for the 3 kW and 7 kW EV chargers and the 4 kW and 6.5 kW PV sizes, the penetration is varied with an increment of 2 LCTs per step until the number of households per phase is reached for each unit separately. The summarized results are shown in Figure 9 – Figure 12.

The previous analysis was conducted for the other two networks (LVRN_2 and LVRN_3) and the results summary for the three networks is given in Figure 8.

Table 3. Daily losses for different LCTs penetration levels (LVRN_1)

<table>
<thead>
<tr>
<th>Number of LCTs</th>
<th>Daily Network Losses [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With EVs</td>
</tr>
<tr>
<td>0</td>
<td>5.59</td>
</tr>
<tr>
<td>20</td>
<td>11.32</td>
</tr>
<tr>
<td>40</td>
<td>23.85</td>
</tr>
<tr>
<td>60</td>
<td>44.19</td>
</tr>
<tr>
<td>80</td>
<td>73.67</td>
</tr>
</tbody>
</table>

The units are affected based on their electrical distance from the transformer and the number of households in each unit in addition to their feeder specifications. Noteworthy, in the previous simulations, the LCTs were divided equally (50% EVs of 3 kW, 50% EVs of 7 kW, 50% PVs of 4 kWp and 50% PVs of 6.5 kWp). On the other hand, the number of LCTs/unit in the previous analysis was determined based on each unit’s number of households. However, in reality, the LCTs power and their numbers can vary randomly across the LVRN. Hence, the power flow simulations were repeated with varying the number of LCTs for each unit to determine the maximum allowable number of EVs charging at the same time for each unit, and the maximum number of PVs that each unit can accommodate without violating the technical constraints. The results are summarized in Table 4. The numbers of LCTs per unit in Table 4 represent the maximum allowable number of LCTs in order not to violate the cable ratings or voltage at each unit which depends mainly on the length, and specifications of each feeder.

Table 4. Maximum allowable number of LCTs per unit (LVRN_1)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Maximum Number of LCTs (EVs)</th>
<th>Maximum Number of LCTs (PVs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(3 kW)</td>
<td>(7 kW)</td>
</tr>
<tr>
<td>U2</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>U3</td>
<td>16</td>
<td>7</td>
</tr>
<tr>
<td>U4</td>
<td>50</td>
<td>22</td>
</tr>
<tr>
<td>U5</td>
<td>22</td>
<td>10</td>
</tr>
<tr>
<td>U6</td>
<td>16</td>
<td>7</td>
</tr>
</tbody>
</table>

The previous analysis was conducted for the other two networks (LVRN_2 and LVRN_3) and the results summary for the three networks is given in Figure 8.
The neutral loss increases, e.g., voltage levels in the aforementioned technical issues. Voltage unbalance can be averaged as +0.025%/kW for U2, 0.061%/kW for U5. Furthermore, the EV charging has a higher impact on the voltage unbalance which can be averaged as +0.05%/kW compared with the PV with +0.037%/kW, while the PV had a higher impact on the voltage limit violation. U2 can safely accommodate only 33.3% EVs (7 kW) of households/phase, 75% EVs (3 kW), 66.6% PVs (6.5 kWp), and 55% PVs (4 kWp). The main violation concerned with U2 is cable overloading. While U5 can accommodate 30% EVs (7 kW), 60% EVs (3 kW), 40% PVs (6.5 kWp), and 55% PVs (4 kWp). All types of violations have been observed for U5.

For the losses, the line losses tend to be linear with the increase of LCTs power, however, the neutral loss increases exponentially. The impact of phase imbalance on the neutral losses is significant as the losses increase proportionally to the increase of LCTs. While, if the LCTs are balanced distributed, the neutral losses should be fixed. It can be concluded that the impact of LCTs on the voltage unbalance is critical and need to be monitored especially for the farthest loaded units as a small number of LCTs operating at the same time on the same phase will result in severe violations that may lead to curtailing the power supply by the DSO.

**c) Impact Assessment Discussion**

The sensitivity analysis proposed in this paper emphasizes the impact of unmanaged LCTs on the LV network operation. The high uptake scenarios of LCTs may lead to critical violations which need to be considered earlier by DSOs to avoid any future problems. As shown in the results, with 2030 LCTs projections (20% PV and 40% EV), the network stability may be threatened as the anticipated increase in LCTs deployment will lead to technical violations. Additionally, the high reverse power flow from PV introduces additional technical issues to the protection equipment that should be considered in future planning. In the previous analysis, the voltage limit was constrained at +10%, -6%, however, some DSOs prefer to set tighter limits based on working practice to ensure the stability and security of the network which should be considered in the impact assessment and determining the hosting capacity.

It is highly advised to consider monitoring each phase separately and consider the voltage unbalance in the assessment as the voltage unbalance can be violated without a voltage magnitude violation occurring. The snapshots presented in the previous results represent the most severe conditions of the day. However, the time-series simulations show that these violations may occur for a longer timespan with a lower level of severity. It was assumed that all the EVs are starting to charge at the same time. Nowadays, multiple EVs may charge at the same time. However, with high EVs penetration (e.g., by 2030), the overlapping in EVs charging may cause severe issues to the network operation. Furthermore, with high LCTs penetrations, phase imbalance will likely occur frequently due to increasing the probability of multiple LCTs operation on a same phase.

DSOs should monitor the LV network carefully as the challenges raised from this level affects the upper network levels in addition to other physical damages that may occur to the low voltage network elements. The technical issues that occur from the high deployment of LCTs in the LV network can be summarized as: 1) Transformer and cables overloading; 2) Node voltage violations; 3) Severe voltage unbalance; 4) High power losses, and 5) Other power quality issues. All the previous issues can be solved using conventional solutions such as upgrading a transformer or underground cables; using reactive power compensators to mitigate the voltage issues, voltage unbalance and enhance the power quality; and reconfiguring the network to mitigate the unbalance impact and losses. All these traditional solutions require high capital expenditure and no one solution can address all the aforementioned technical issues.

The most effective smart solutions that can be applied are BESS and demand side management programs. BESS have attractive...
potential in solving network challenges. However, the planning and operation of BESS should be properly defined. In the upcoming section, the planning and operation of a community BESS to relieve network congestion imposed from the high penetrations of LCTs will be investigated.

5 The role of battery energy storage systems

In this section, a solution to the LCTs challenges is introduced based on BESS. As discussed previously, conventional reinforcements have limited applications and high capital expenditures. However, BESS have the capability to solve all the LVRN violations. The location of the BESS is crucial to achieve maximum utilization. In the LVRN, the BESS can be installed at the transformer bus to mitigate the transformer overloading as well as the VU at the transformer bus. Yet, other issues such as cable overloading, node voltage magnitude imbalance violations, and high energy losses will still exist.

While the BESS could be installed on the feeder of each congested unit to solve all the LVRN problems, more beneficially it should be located at the end of the feeder for maximum performance [17]. In addition, the connection configuration of BESS should also be identified as the BESS can be connected as follows: 1) to the congested phases only; 2) to the three phases using three-phase power conversion system (PCS), and 3) to the three phases using single-phase PCS with/without a phase selector. In this paper, it is assumed that the BESS can inject and absorb power to/from the three phases, this can be done by connecting a single BESS to the three phases through a three-phase PCS or by connecting three separate BESS to each phase individually. This section introduces the adopted BESS model as well as the proposed BESS sizing and scheduling algorithms.

5.1 BESS System Model

Various models can be used to identify the BESS operational constraints. In this paper, a detailed generic model is adopted that can be used for any type of BESS technologies considering realistic parameters which explained as follows:

1) BESS Power Rating: The discharged power \( P_{t,b}^{\text{dis}} \) or charged power \( P_{t,b}^{\text{ch}} \) from the BESS at any time-point \( t \) must not exceed the BESS predefined rating.

\[
P_{t,b}^{\text{max}} \leq P_{t,b}^{\text{dis}} \leq P_{t,b}^{\text{BESS}} \in \{P_{t,b}^{\text{dis}}, P_{t,b}^{\text{ch}}\} \tag{5}
\]

2) BESS System efficiency: The power imported \( P_{t,b}^{\text{ch}} \) or exported \( P_{t,b}^{\text{dis}} \) from/to the grid by BESS at any time is affected by input/output efficiencies of the BESS \( \eta_b^{\text{BESS}} \) and the power conversion system (PCS) \( \eta_b^{\text{PCS}} \).

\[
\eta_b = \eta_b^{\text{BESS}} \times \eta_b^{\text{PCS}} \quad \eta_b^{\text{PCS}} = \frac{\eta_b^{\text{eff}}}{\sqrt{\tau}} \tag{6}
\]

\[
P_{t,b}^{\text{dis}} = \eta_b^{\tau} \cdot P_{t,b}^{\text{dis}} \quad P_{t,b}^{\text{ch}} = \eta_b \cdot P_{t,b}^{\text{ch}} \tag{7}
\]

Where \( \eta_b^{\text{eff}} \) is the BESS round-trip efficiency.

3) State of Charge (SoC): SoC is the percentage measurement that indicates the available capacity still in the BESS. The SoC must be maintained within the pre-defined limits to maintain the BESS capacity over longer periods.

\[
SoC_{t,b}^{\min} \leq SoC_{t,b} \leq SoC_{t,b}^{\max} \tag{8}
\]

\[
SoC_{t,b} = SoC_{t-1,b} + \frac{P_{t,b}^{\text{ch}} \eta_b^{\tau}}{E_b^{\text{cap}}} - \frac{P_{t,b}^{\text{dis}}}{E_b^{\text{cap}}} \tag{9}
\]

Where \( \tau \) is the time interval period such that \( \tau = \frac{24}{n_p} \) \( n_p \) is the number of points which is determined based on the data resolution (24 for hour, 48 for 30-minute, and 144 for 10-minute), \( E_b^{\text{cap}} \) is the BESS nameplate capacity, and \( E_b^{\text{cap}} \) is the BESS usable capacity.

4) PCS Rating: At any time-point, the apparent power handled by the PCS should not exceed its rating.

\[
S_{t,b}^{\text{PCS}} \leq S_{t,b}^{\max} \tag{10}
\]

\[
S_{t,b}^{\text{PCS}} = \sqrt{(P_{t,b}^{\text{PCS}})^2 + (Q_{t,b}^{\text{PCS}})^2} \tag{11}
\]

5) BESS Sizing

The BESS size should be determined wisely to avoid under/over sizing. Additionally, the BESS size should be determined based on the delivered applications and should consider the future projections of the LCTs and demand for a network. These projections should be identified by the network operators based on their forecasting for each network. In this paper, the objective of the BESS is to maintain the network constraints (VU, node voltage, and line flow) within the acceptable limits and the 2030 LCTs uptake scenario is adopted in determining the BESS size in the case study. Determining the BESS size requires OPF calculations to obtain the BESS size subject to the network technical constraints. Different approaches have been introduced to tackle the OPF problem through linearization, convex relaxation, or by converting the OPF constraints into soft constraints using penalty functions [22]. In this paper, the OPF problem is treated as a black-box optimization [51], where the network technical constraints (VU, node voltage and line flow) are modelled in the objective function as a feasibility problem, which avoids the use of hard constraints and reduces the computation time of solving the OPF problem. The goal of this black-box optimization is to solve all network violations using minimum BESS capacity which is mathematically formulated as a multi-objective function using the weighted sum method and normalized into a mono-objective function using the consequent upper-bound approach [52], expressed for a BESS installed at a specific feeder/unit (u) \( v \in T_u \) as:

\[
\min \left( \sum_{t=1}^{T_u} \left( w_{1,t} F_1(x) + w_{2,t} F_2(x) + w_{3,t} F_3(x) + w_{4,t} F_4(x) \right) \right) \tag{12}
\]

\[
F_1(x) = \sum_{t=1}^{T_u} c_{\text{v},t} [V_{u,t} > V_{u,0}] \tag{13}
\]

\[
F_2(x) = \sum_{t=1}^{T_u} \sum_{p=1}^{3} c_{\text{v},t,p} [V_{t,u,p} < 0.94 \lor V_{t,u,p} > 1.1] \tag{14}
\]

\[
F_3(x) = \sum_{t=1}^{T_u} \sum_{p=1}^{3} c_{\text{v},t,u,p} \left[ I_{t,u,p} > I_{u,p} \right] \tag{15}
\]
\[ F_d(x) = \sum_{t=1}^{T_d} \sum_{\beta=1}^{3} x_{t,\beta,t} \tau \]  
(16)

Note that [\( \cdot \)] in Eq. (13) – Eq. (15) are Iverson brackets (the Iverson bracket is equal to 1 when the logical condition enclosed is true and 0 otherwise). \( \emptyset \) represent the phase such that \( \emptyset \in \{1,2,3\} \). The multi-objective function in Eq. (13) consists of four weighted sub-functions. \( F_1(x) \) represents the VU function. \( F_2(x) \) represents the voltage violations, where \( V_{\text{LCT},\emptyset} \) is the phase voltage. \( F_3(x) \) represents the cable loading, where \( I_{\text{LCT},\emptyset} \) is the phase current and \( I_{\text{LCT}} \) is the feeder maximum capacity. \( F_4(x) \) represents the total used BESS capacity over the dispatch horizon (charging/discharging). The weights were varied, and the optimal results were obtained using the following weights: \( w_1 = w_2 = w_3 = 0.61 \) and \( w_4 = 1 \). The constraints functions \( F_1(x) \), \( F_2(x) \), and \( F_3(x) \) are given higher weights compared to the BESS size as they must be maintained within the acceptable limits. \( c_{\text{LCT},\emptyset} \) and \( c_{\text{Cab}} \) represent violations of VU, node voltage, and cable rating respectively. \( T_{\text{d}} \) is the optimization horizon such that \( T_{\text{d}} \in \{7,7,2\} \), where \( T_{\text{d}} \) is the discharging horizon and \( T_{\text{c}} \) is the charging horizon. \( P_{\text{max}}^{\text{cap}} \) represents the maximum value of the objective function for the normalization purpose such that \( m \in \{1,2,3,4\} \). The VU is considered as a violation if the VU is larger than 2, the node voltage violation is considered when the node voltage exceeds \( 230 +10 / -6 \% (0.94 \text{ pu} - 1.1 \text{ pu}) \), and the cable loading is considered as a violation when the line flow exceeds the cable ampacity. The optimal values of \( F_1(x), F_2(x), \) and \( F_3(x) \) are zero which represents no violations.

The aim of this BESS sizing formulation is to find the minimum BESS size that solves the network violations. The optimization solver initializes a set of decision variables \( x \) representing the BESS power \( P_{\text{BESS}} \) for each phase during each mode (charging/discharging) at each time-point of the day such that \( x_{\text{LCT},\emptyset} = (x_{t,\beta,t}, x_{t+1,\beta,t} \ldots x_{t+1,\beta,t}) \). Within each mode, the decision variables are adjusted to consider the BESS system efficiency using Eq. (7). Afterwards, these variables are entered into a time-series unbalanced three-phase power flow routine. The power flow results are then used to evaluate the objective function Eq. (12) as black-box. In case of no violation observed, the value of objective function Eq. (12) is zero. After the optimization horizon ends, the solver updates the decision variables to optimally obtain the minimal needed power to be distributed over the charging/discharging horizons to satisfy the objective function. The lower bounds of these variables are set to zero, while the upper bounds should not be limited as the aim of this method is to find the BESS size and rating. However, a specific value can be set based on the available BESS ratings or based on the DSO’s preference to reduce the computation time by decreasing the search space.

After the optimizer converges, the daily power dispatch values are used to determine the daily BESS usable capacity \( E_{\text{BESS}}^{\text{us}} \) needed during both modes (charging/discharging) considering the BESS system efficiency Eq. (7) based on the consecutive period with highest energy dispatch using Eq. (17), afterwards the BESS nameplate capacity \( E_{\text{BESS}}^{\text{cap}} \) is determined in each day based on the SoC pre-defined limits using Eq. (19), whilst the maximum power dispatched within all the day is considered as the BESS power rating using Eq. (18).

\[ E_{\text{BESS}}^{\text{us}} = \max \left( \sum_{t=1}^{T_d} \sum_{\beta=1}^{3} x_{t,\beta,t} \frac{\tau}{\eta_b}, \sum_{t=1}^{T_c} \sum_{\beta=1}^{3} x_{t,\beta,t} \frac{\eta_b}{\tau} \right) \]  
(17)

\[ p_{\text{max}} = \max \left( \sum_{t=1}^{T_d} x_{t,\beta,t}, \sum_{t=1}^{T_c} x_{t,\beta,t} \right) \]  
(18)

\[ E_{\text{BESS}}^{\text{cap}} = \frac{E_{\text{BESS}}^{\text{us}}}{\eta_{\text{BESS}}} \]  
(19)

Finally, after determining the daily values of BESS capacity and rating, the highest values amongst all the simulation days are considered as the BESS specification (capacity in kWh and rating in kW). Note that, the proposed BESS sizing algorithm considers only the BESS active power, and it is assumed that the BESS PCS is operating on unity power factor in agreement with the DSO of Northern Ireland regulations [53] due to the impact of reactive power on rising the feeder voltage. The proposed BESS sizing algorithm flowchart is illustrated in Figure 13, and the algorithm requires the following inputs:

- Time-series data of demand and LCT (for single or multiple days according to the available data).
- Pre-defined dispatch horizons for each day (i.e., from 12:00 hr to 17:00 hr for charging, and from 18:00 hr to 23:00 hr for discharging).
- BESS location, DoD/SoC limits, and efficiency.
In the power flow calculations, the BESS decision variable at the BESS node is treated as a negative load during the discharging mode and as a positive load during the charging mode. As the network constraints are modelled in the objective function in Eq. (12), hence the proposed BESS sizing algorithm is unconstrained optimization which can be solved easily using many available off-the-shelf optimization solvers.

3) BESS Scheduling

In order to evaluate the impact of BESS in different operating conditions, a scheduling algorithm is introduced. As the BESS size and rating have been settled from the previous sizing phases, Eq. (5) is adjusted to the following Eq. (2):

$$\min_x \left( \frac{w_1 F_1(x)}{F_1^{\max}} + \frac{w_2 F_2(x)}{F_2^{\max}} + \frac{w_3 F_3(x)}{F_3^{\max}} \right)$$

For the fourth function $F_4(x)$ is written in this way to differentiate between the neutral and phase losses. $F_4(x)$, $F_5(x)$, and $F_3(x)$ represent the LVNR technical constraints described in Eq. (1)–Eq. (15).

The fourth function $F_4(x)$ is related to minimizing the VU and has been written in this way to differentiate between this function and the fourth function $F_3(x)$ of the BESS sizing algorithm. $F_4(x)$ aims to reduce the neutral losses, where $R_u^n$ represents the feeder/unit neutral resistance and $I_{u,n}$ is the neutral current. $F_5(x)$ aims to reduce the phase losses, where $R_{u,p}$ is the feeder/unit phase resistance for each phase. The proposed scheduling algorithm aims to distribute the BESS power optimally over the three phases during the daily dispatch horizons by initializing a set of decision variables subject to the BESS system efficiency Eq. (7) and the BESS power rating Eq. (5), however, because the BESS is connected to three phases, Eq. (5) is adjusted to the following Eq. (24).

$$\sum_{t=1}^{3} x_{t,u,0} \leq P_{b}^{\text{max}} \ ; \ x_{t,u,0} = B_{t,u,0}$$

Eq. (24) and the BESS SoC Eq. (8) are formulated as hard constraints. The optimization solver evaluates the objective function (Eq. (20)) subject to these constraints. The proposed BESS scheduling algorithm follows the steps illustrated in Figure 14 and requires the same inputs of the BESS sizing algorithm in addition to the BESS capacity and power rating.
trip efficiency ($\eta^{tr}_{LCT}$) is assumed as 90% which were imported from an actual project [56]. In addition, the 2030 uptake scenarios of LCTs given in Section 2 (d) are adopted (20% PV penetration and 40% EV penetration).

The proposed BESS sizing and scheduling algorithms are formulated as black-box optimization, which requires a derivative-free optimizer [51]. Some derivative-free solvers were tested, and the best results were obtained using the Genetic algorithm (GA) for the BESS sizing and the NOMAD solver [57] for the BESS scheduling.

NOMAD is a derivative-free global optimization solver that implements the MADS (Mesh Adaptive Direct Search) algorithm [58], which is a development of the Generalized Pattern Search (GPS) algorithm. NOMAD is a direct search, iterative method that has three processes in each iteration: poll, search, and update. It evaluates the objective function by generating trial points lying on a mesh using the poll and search. The results of these evaluations are then examined and used to generate new trial points using the update process. A variable neighborhood search algorithm is integrated into NOMAD to prevent the algorithm from being trapped in local optima [59]. NOMAD has been adopted in this work due to its effectiveness in providing optimum solutions to the BESS scheduling optimization problem in a reasonable processing time. In addition, it has proven its effectiveness in different optimization problems for commercial and non-commercial applications [57].

For the BESS sizing, different GA generations were tested, and it was observed that the objective function does not change significantly after 80 generations. For the BESS scheduling, the following NOMAD parameters are assigned: starting points of zeros, and stopping criteria of max execution time of 1000 seconds, and relative/absolute convergence tolerances of 1e-7.

The GA was utilized using the optimization toolbox of MATLAB and the NOMAD was implemented in MATLAB through OPTI Toolbox [60].

a) BESS sizing results

The proposed BESS sizing algorithm is designed to simulate a period of time (few days to years) and to determine the optimal BESS size amongst the simulated days. As shown in the LCTs impact assessment, the violations vary according to the LCTs penetrations and assumption used in analysis such as the distribution of LCTs across the phases, and the LCTs patterns. In this paper, a case study is presented based on a set of assumptions to evaluate the BESS sizing algorithm. As there is a paucity in the available measurements for the test network, demand measurements of a single day (23/8/2019) in 10-minute resolution are selected for the BESS sizing which represents the date with maximum demand among the available measurements. For the LCTs, ideal PV generation profiles are used, while different EV patterns are generated probabilistically using the EV charging pattern model described in Section 2 (b). However, to tighten the EV charging during peak time to consider the severe violations, the start time of EV charging is constrained between 16:00 hr to 22:00 hr conditioned by the CDF in Figure 3. Furthermore, to consider the unbalanced impact, the LCTs are assumed to be distributed on U5 phases as follows (60% of the LCTs on Phase A and 40% on the other phases equally).

The pre-defined scheduling horizons are assigned as: from 12:00 hr to 17:00 hr for charging ($T_c$) which represents the mid-day period with high PV generation and from 18:00 hr to 23:00 hr for the discharging ($T_d$) which represents the evening peak with high EV charging. Probabilistic simulations were implemented by varying the EV patterns 20 times and the BESS sizing summary results are shown in Figure 15.

As shown in Figure 15, as the PV and demand profiles are fixed, the BESS specifications (capacity/power) vary based on the EV charging patterns. The more the EV charging overlaps, the higher BESS capacity needed due to their impact on threatening the LVRN technical constraints. The highest BESS size achieved is 140 kWh / 29 kW. However, this represents the case with the highest violations which unlikely to happen regularly because the EV charging was constrained to specified times to simulate violations during the peak. However, in reality, EV charging varies across the day. In addition, the distribution of LCTs over phases was pre-settled, however, it may differ in practice. The selection of BESS specification amongst the results is left to DSOs based on their projections and assumptions. However, it is recommended to simulate a long period based on DSO assumptions to determine accurately the BESS size using the proposed sizing algorithm. From the previous results, an average BESS specification can be determined as 47 kWh / 19 kW.

b) BESS scheduling results

To evaluate the effectiveness of the proposed BESS scheduling algorithm, the following assumptions are adopted. One week of demand measurements are used from 23/8/2019 to 29/8/2019. For the LCTs profiles, two actual PV profiles for the following sizes (4 kWp and 6.5 kWp) are adopted from [37] for the same week. While different EV charging patterns were generated from the pre-explained model in Section 2 (b). BESS specification of 47 kWh / 19 kW has been used as an average of the BESS sizing results. To simulate random LCTs distribution over phases, the loading of LCTs over the three phases of U5 were distributed randomly for each day as:

$$ r_0 = \text{rand } [0,1] ; \quad \gamma_0 = \frac{r_0}{\sum_{\theta=1}^{3} r_0 } ; \quad \sum_{\theta=1}^{3} \gamma_0 = 1 $$  \hspace{1cm} (25)
Where $r_∅$ is a random number generated between 0 and 1 for each phase, and $γ_∅$ is the LCTs loading fraction for each phase such that the summation of all loading fractions equals 1. The results of the one-week simulations before and after the BESS scheduling are illustrated in Figure 16 and Figure 17, while the improvements summary is given in Table 5.

As shown in Figure 16 – Figure 17, and Table 5, during the peak, the BESS managed to shave the peaks and solve all the violations represented in VU, undervoltage, and cable overloading. During PV generation, the BESS reduced the reverse power flow by increasing the feeder self consumption in addition to reducing the overvoltage and the voltage unbalance. For the days with no violations, the BESS optimized the network performance by regulating the VU and phase voltage as well as reducing the stress on the feeders and minimizing the phase and neutral losses. To summarize the average improvements over one-week, the daily loss in energy was reduced by 12% for phases, and 27.4% for neutral, the VU was optimized by 21%, the voltage was regulated by 13%, and the cable loading during peak was regulated by 12%.

c) BESS degradation

The proposed approach preserves the BESS lifetime by using only 70% of the BESS actual capacity that represent the DoD, which has been shown to maintain the number of BESS cycles defined by the manufacturers [54], [55]. However, in order to evaluate the detailed impact of the proposed BESS scheduling on the degradation, the semi-empirical Li-ion cycling degradation model in [54] has been adopted to quantify the BESS state of health (SoH) at the end of lifetime. The BESS...
SoC profile was obtained from the one-week simulation in Figure 17 and repeated for one-year. Afterwards, the rainflow counting algorithm [61] has been used to analyze the SoC profile and extract the data required for the degradation model. The cycling ageing throughout one-year is illustrated in Figure 18.

Table 5. Average improvements for the one-week case study

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<td>20.529</td>
<td>9.946</td>
<td>13.897</td>
<td>35.493</td>
</tr>
</tbody>
</table>

Figure 18. BESS cycling degradation throughout one year of operation using the proposed BESS scheduling algorithm.

The results from the ageing model show that the BESS capacity degrades by 3.05%/year with 365 full cycles. By scaling for 10 years of operation which is the warranted lifespan of Li-Ion BESS [62], the BESS is assumed to reach an SoH value of 69.51%. This value represents the SoH (residual capacity) at the end of 10 years of operation which is adequate as the BESS considered to reach the end of life when the residual capacity reaches 60% – 80% [54], [63]. The SoH of 69.51% proves the effectiveness of the proposed scheduling algorithm in preserving the BESS capacity throughout its warranted lifetime. Note that, in the previous assumption, the degradation was calculated assuming that the BESS operates all the year according to the simulated one-week case study. However, in practice, the BESS may not be required to be used completely in daily basis. Thus, the expected BESS SoH at the end of a lifetime might be higher in reality.

d) Discussion

The previous results show the effectiveness of the BESS and the proposed scheduling algorithm in solving all the technical violations in addition to optimizing the operation of the LVNR. The use of BESS in the LVNR has proven to be very attractive due to their wide applications. In addition, in the previous simulations, it was assumed that the BESS PCS is operating on a unity power factor, this is due to the reactive power effect on raising the system voltage, the majority of distributed generation and microgeneration units in Northern Ireland are not permitted to inject reactive power and they are operated on unity or leading power factor [53]. Equipping the BESS with a proper PCS/inverter will allow for absorbing/injecting reactive power which will be beneficial in the case of over/under voltage in addition to enhancing the power factor and quality. However, managing the reactive power should be coordinated with the DSO to avoid affecting the network constraints and supply security.

In the previous results, one BESS (47 kW / 19 kW) was installed at the end of the U5 feeder, this BESS can be replaced with three BESS of (16 kW / 7 kW). Each one of these BESS should be connected to a phase selector to be able to inject and absorb from the three phases. On the other hand, these units can be replaced by behind the meter units, by equipping only 25% of the households in U5 with a BESS with 7 kW / 3 kW. However, in this case, the connections should be balanced across the phases and the DSO should have full management of these units. An agreement can be settled between the DSO and customers in which the DSO can have full access to these BESS by incentivizing the customers through offering a single payment as a part of the capital cost or fixed small yearly/monthly payments. Recent findings from the Distributed Storage & Solar Study by Northern Powergrid [64], have shown the effectiveness of residential BESS in shaving the peak demand averagely as well as reducing the impact of residential solar PV export power.

It is worth mentioning that the proposed BESS scheduling algorithm should be implemented on a look-ahead basis using forecasted data, and hence, it can be used for short/long term planning. In this paper, the scheduling results were determined assuming perfect foresight in order to evaluate the proposed scheduling algorithm. However, proper forecasting model should be used in practice. Moreover, real-time operation methodologies should be investigated to overcome the uncertainties associated with forecasting, which can be considered an extension of this work. Examples of applicable BESS real-time methods have been introduced in [26], [27].

7 Conclusion

This paper investigated the impact of LCTs such as EVs and PVs on the low voltage unbalanced residential networks. Different LCTs penetrations were tested on real LV residential networks located in Northern Ireland for balanced and unbalanced distribution of LCTs over the three phases. The assessment was conducted by evaluating various critical technical indices including voltage unbalance, phase voltage, line flow, and phase/neural losses. The results show that with high penetration of unmanaged LCTs, the network security and power quality will be threatened. A flexible solution based on the community BESS was introduced by proposing a sizing algorithm to determine the proper BESS size with minimum...
investment to be installed at the feeder’s end node that supports the network during congestion. The scheduling of BESS was also introduced via a scheduling algorithm to solve the network violations in addition to improving the network power quality. The community BESS proved its capability in enhancing the network performance and flexibility which supports the secure integration of further LCTs.

The payments that should be received by the BESS owners are not yet established by the DSO in Northern Ireland. The BESS payments should be profitable to encourage the BESS investors to participate in supporting the LVRN. Usually, these payments will be structured according to the type of the service as well as the availability and utilization. DSOs should introduce profitable commercial contracts to attract and encourage energy investors to participate in the BESS to accelerate the transition towards the net-zero target and low carbon communities. The main goal of this paper is to assess the technical impacts of high LCTs penetration and the role of community BESS in providing different services to support the network operation. However, further investigations are required to determine the specific demand of each service (e.g., voltage unbalance, voltage regulations, peak shaving, ... etc.) and the BESS stacked revenues in the low voltage networks, which is considered as future research.

Behind the meter units can be considered as a very attractive option, however, these units require appropriate monitoring and management. Unmanaged residential BESS can act as additional demand during charging and as a generation during discharging and so can introduce the same technical issues to the LVRN operation discussed previously in this paper. Hence, proper coordination and management frameworks should be introduced to achieve maximum utilization of these resources by the DSOs and assuring the profitability of customers, which is considered as future research. Demand side management can also assist in mitigating the LCTs technical problems. This can be achieved by offering incentives to pre-defined customers according to their locations in return for their assistance in supporting the LVRN operation by reducing/increasing their demand at specific times according to signals from the DSOs. Additionally, bespoke time of use tariff structures can also indirectly enforce customers to reduce their consumption during the peak and increase their consumption during the PV generation. This will help in mitigating the demand peak and reverse power flow. However, other issues may be introduced such as voltage unbalance. Hence, dynamic tariff structures can be considered as a good option. The tariff structure can also be varied over the households in the LVRN to achieve a balance in the consumption across the day.

8 Acknowledgements

The authors would like to thank NIE Networks for their valuable support and providing the data used in this paper. This research is part of SPIRE 2 project (Grant No: IVAS038) supported by the European Union’s INTERREG VA Programme, managed by the Special EU Programmes Body (SEUPB). The views and opinions expressed in this document do not necessarily reflect those of the European Commission or the SEUPB.

9 References


