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Electrical distribution network challenges of rapid electric vehicle adoption in rural areas surrounding urban centres: Case study in Ireland

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ABSTRACT

Rural regions, with lower population density, typically show higher car dependency leading to greater vehicle ownership, longer trips and higher travel frequencies. As a result, transport electrification of rural areas will strongly influence per-capita carbon reduction targets. This work considers capacity issues on low voltage distribution networks for uptake of large penetration level of electrified transport in rural areas. We use Ireland as a particular case study as 36% of the population live in rural areas, but account for ∼55% of transport emissions. We synthesize EV charging load profiles for typical rural residential clusters under increasing EV penetration levels up to 100%. Results indicate that synchronized home charging during off-peak hours (02:00–04:00) is a key issue leading to voltage drops of up to 12% from 230 V and substantial transformer temperature rises and cycling. Smart charging including scheduling, queuing services, and flexible demand strategies offers significant potential to mitigate thermal stress, reducing peak temperatures by almost 80°C depending on the scenario and defer costly grid reinforcements. Urgent collaboration between policy makers, EV charger manufacturers and aggregators, and distribution system operators, and energy retailers is required to implement flexibility and offset future costs. Typically considered in the context of dense urban areas, we demonstrate that smart charging can also be of practical benefit in rural regions.

1. Introduction

Despite recent improvements, Irelands transport sector remains overwhelmingly dependent on fossil fuels, with 94% of energy coming from fossil fuels in 2023 [1]. It accounts for 43% of end user energy demand, and 21.5% of total greenhouse gas (GHG) emissions. Private cars alone contribute almost 50% of these emissions, making the decarbonization of private transport a key element in achieving net-zero targets [2]. The number of Battery Electric Vehicles (BEVs) in Ireland has been increasing annually over the past decade, from just under 500 new registrations in 2015 to a peak of almost 24,000 in 2023 and the goal to have 180,000 EVs on the road by the end of 2025 could plausibly be reached by the end of this year [3,4]. Currently, there are more than 2.25 million private vehicles registered on Irish roads with an estimated 140,000 plug-in hybrid (PHEV) and fully battery electric vehicles (BEV), representing 6% of the fleet in total [5,6]. For 2030, it is the government's ambition, articulated in Climate Action Plan (CAP) 24, to have 845,000 private electric vehicles (EV) on Irish roads, that is BEVs and PHEVs, which would represent 30% of the projected fleet size [3]. EVs should also make up 100% of new registrations effectively saying there should be no new internal combustion engine vehicles (ICE) sold and registered after 2029 [3].

Currently, the highest EV concentration is in and around the Pimrary city (Dublin), largely due to higher population density and a greater proportion of affluent households [6]. The spatial distribution of EVs by 2030 can be expected to depend on efforts of enhancing public and household charging infrastructure, availability of EV purchase grants, cost of new EVs and lifecycle cost of ownership and ease of driving [7]. Car ownership per household is already lower in urban areas and efforts to increase public transportation availability could lead to further decreases. This could potentially shift EV concentration outside of urban settings and more into sub-urban and rural belts in the event of mass uptake. Car dependency and induced car ownership are more pronounced in rural areas where less transport mode alternatives exist to abate the private vehicle and households with 2 or more private cars are common [8]. The average trip distance in rural areas (16.7 kilometres) is

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also twice as high as in Dublin City and its suburbs (7.7 kilometres) and the car is the dominant mode of transport with an 80% share among most age groups [9]. In Ireland, around 36% of the population live in Rural areas, but they account for ∼55% of transport emissions [10]. Increased EV adoption in rural areas could therefore yield greater carbon emissions savings per vehicle compared to urban areas and should be facilitated.

Studies show that up to 80% of EV charging is performed at home and that access to home charging is one of the most important requirements for people to adopt an electric vehicle [11–13]. Considering the projected increase of BEV registrations and the importance of cars in rural settings, this raises relevant questions about the ability of the underlying electrical distribution infrastructure in rural areas to scale and to accommodate the increased requirements over the next five years and beyond. Initial infrastructure efforts have focused on the installation of public charging networks to align with EU regulation through the Alternative Fuels Infrastructure Regulation (AFIR) [14]. In moving on from initial implementation to widespread adoption, focus needs to shift from public charging infrastructure to strengthening resilience and increasing capacity of the low-voltage (LV) distribution network. Additionally, changes in residential electrical load profiles due to the electrification of heating and the installation of solar photovoltaics (PV) compound stress on the distribution system. We are already starting to see strain with a 22% increase in total power cuts between 2022 and 2024, and many substations at full capacity leading to lengthy delays in new connections [15]. Due to the exponential nature of the increase on BEV, time to act is short and we will soon find ourselves in a situation where adoption of EVs is limited due to distribution system capacity constraints. Recognising this, the Commission for Regulation of Utilities (CRU) has published its National Energy Demand Strategy (NEDS) in 2024 which indicates that significant investment is needed particularly in the distribution network to support this change [16].

This study examines how rising EV adoption interacts with the capacity limits of Ireland's low-voltage (LV) distribution network, with particular attention to rural commuter zones where car dependence is high and public transport alternatives are limited. Rural in this case refers to all areas surrounding a central settlement of 1500 or more people; such areas cover 96% of the country and house about 36% of the population in Ireland. We map the current spatial distribution of battery-electric and plug-in hybrid vehicles and areas of expected growth in uptake against available data on LV network capacity to identify where adoption and grid constraints overlap. To understand the local impacts, we model a representative rural cluster of a single-phase pole-mounted transformer serving six dwellings—a configuration common in Ireland's countryside. The six-home scenario reflects typical historical sizing and LV transformer loading and provides a tractable case for quantifying the impact of different uptake levels of electrified transport. Using travel-survey data on trip frequency and distance, together with power-demand profiles from common EV models, we generate household charging profiles and simulate their effects on voltage regulation and LV transformer temperature and lifetime. We also include indicative scenarios with other low-carbon technologies (LCT) such as heat pumps and rooftop solar photovoltaics (PV), as these are increasingly promoted for decarbonisation and are likely to coincide with EV uptake. Our results show that simultaneous night-time charging, encouraged by off-peak tariffs, produces much higher and prolonged current peaks than traditional household demand and can accelerate transformer ageing. Extensive targeted reinforcement of LV transformers and lines will therefore be necessary in many rural locations as EV penetration grows. At the same time, our modelling indicates that coordinated smart charging and other forms of flexible demand strategies could defer some of these upgrades by spreading charging over a wider time window, thereby extending the useful life of existing assets and allowing smaller replacement sizes. Such measures offer a cost-effective bridge while longer-term, higher-capacity infrastructure investments are planned and implemented. This paper makes the following contributions:

- A transformer-level LV network analysis is provided, focusing specifically on Irish rural fringe clusters surrounding urban centres.
- Quantification of voltage deviations and transformer hot-spot temperatures and thermal stress under high EV penetration scenarios using realistic characteristics of pole-mounted LV transformers between 15 kVA and 100 kVA as they are presently used in Ireland. To assess charging requirements, trip data from the Irish National Transport Authority (NTA) is analysed to estimate daily charging requirements.
- Assessment of the effectiveness of sequential and time-shifted smart charging strategies in mitigating transformer overload and voltage quality issues.
- Identification of policy-relevant implications for tariff harmonization and rural network reinforcement planning to support EV uptake, PV penetration and heat pump installations following the Irish climate ambition.

While previous studies in an Irish context have examined EV market impacts regarding GHG emissions [17,18] or charging behaviour at early stage market penetration [19], limited attention has been given to small rural clusters characterized by low diversity, long feeder lengths and small transformer capacities. Existing works on the impact of EVs on LV networks in other countries assume different charging behaviour [20] or different transformer sizes in rural settings [21] and therefore do not translate to the Irish case. This study addresses this gap by providing a detailed case study of a representative rural Irish cluster, based on population and network distribution, trip data, realistic transformer characteristics and charging assumptions based on current electricity tariffs to quantify voltage deviations and transformer thermal stress under realistic adoption scenarios for Ireland.

2. Research process and methodology

The research was conducted in several stages. First, a literature review was carried out to examine existing contributions studying the impacts of EV adoption on rural LV distribution grids. In addition, Irish policies and targets relating to EV deployment and LV grid infrastructure were reviewed. In the second stage, a spatial analysis was performed using QGIS to investigate the geographic distribution of EV uptake and the topology of the LV grid in rural areas in Ireland. In the third stage, a representative case study on a rural cluster consisting of six residential homes supplied by a pole-mounted transformer was modelled using PowerWorld Simulator. Household electricity demand profiles from a rural Irish dwelling were combined with characteristic load profiles for EV charging, heat pumps, and solar PV generation to simulate realistic scenarios of EV and LCT adoption. AC power flow simulations were then performed to evaluate the impact of these technologies on transformer loading and network performance. Typical pole-mounted transformer characteristics and thermal loading frameworks from IEEE and IEC standards were used to develop a thermal model of the transformer. The equations and derivation of the thermal model and simulation parameters is explained in detail in the supplemental section A. The thermal model was applied using MATLAB to analyse the thermal response of the transformer under different load scenarios and based on the simulation output. Lastly, coordinated EV smart charging strategies were modelled to investigate their potential to reduce peak demand and mitigate transformer overloading. These scenarios were compared with uncontrolled charging cases in order to assess the effectiveness of smart charging in improving network operation and derive policy implications. The research stages are illustrated in Fig. 1.

3. Background

3.1. The distribution system topology

The capability of the electrical infrastructure to accommodate

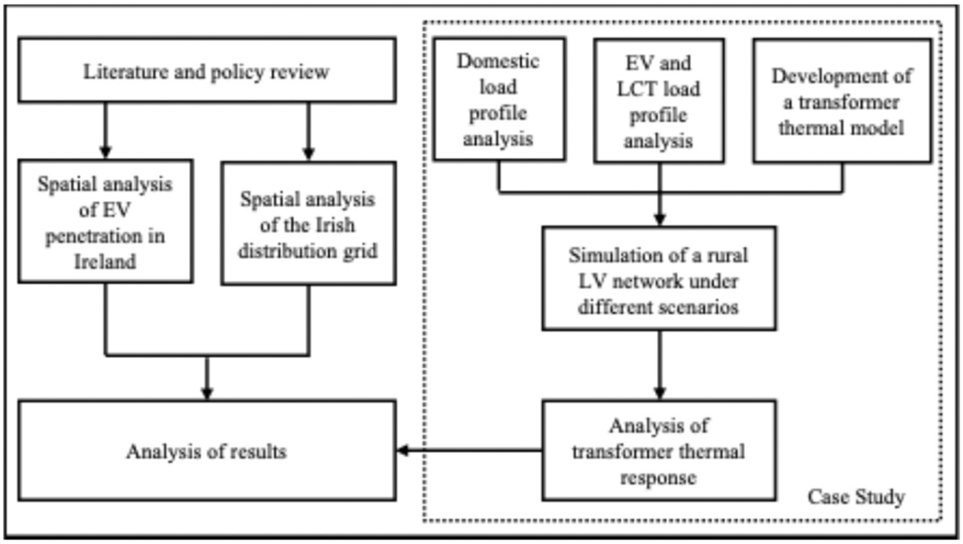

Fig. 1. Overview of the research methodology and key stages of the study.

increasing loads from EVs is governed by the network assets and grid topology. The Irish distribution system is hierarchically structured as a radial network with high voltage substations that are connected to the transmission network (110 kV, 220 kV) and serve as parent stations to a network of child substations. On the customer level and particularly in rural Ireland, individual residential customers are fed from medium voltage (10 kV, 20 kV) lines which are converted to low voltage (230 V single-phase, 400 V 3-phase) using pole or cabinet transformers with capacities in the range of 15–100 kVA. Due to the dispersed population in Ireland and high levels of electrification, the Irish distribution network length per capita is four times the European average, consisting of 2.1 million wooden poles, 150,000 km of overhead lines, 22,000 km of underground cable and 133 substations of 110 kV capacity [22,23]. A schematic of the network hierarchy in Co. Meath as well as the northern Dublin area is shown in Fig. 2(a). This is generated from ESB Network's *Availability Capacity Map*, and it reflects the dense infrastructure around Dublin Bay and how the number of grid assets decreases when moving out of Dublin and into sub-urban and rural areas. While the green lines in Fig. 2(a) represent hierarchical connections rather than actual power lines, it still becomes clear that the distance between individual substations increases towards the rural regions, affecting line lengths and related resistance and potential voltage regulation and phase imbalances. The colour of the dots represents the hierarchy level of a particular substation within their cluster. Green dots represent a transmission grid connection, followed by blue, pink and yellow dots moving down in the hierarchy towards the LV assets. Rural towns and villages are typically fed from the 10 kV or 20 kV MV lines as shown in Fig. 2(b). Cabinet substations are used in towns or housing estates, with pole mounted transformers directly connected to a single phase of the MV line as the dominant form of connection for rural roadside clusters. Small businesses and industry may have a 3-phase connection directly to the MV line. The MV/LV substations convert the medium-voltage to low-voltage (400 V 3-phase, 230 V single-phase) using pole or cabinet transformers with capacities in the range of 15–200 kVA. Usually 15–33 kVA

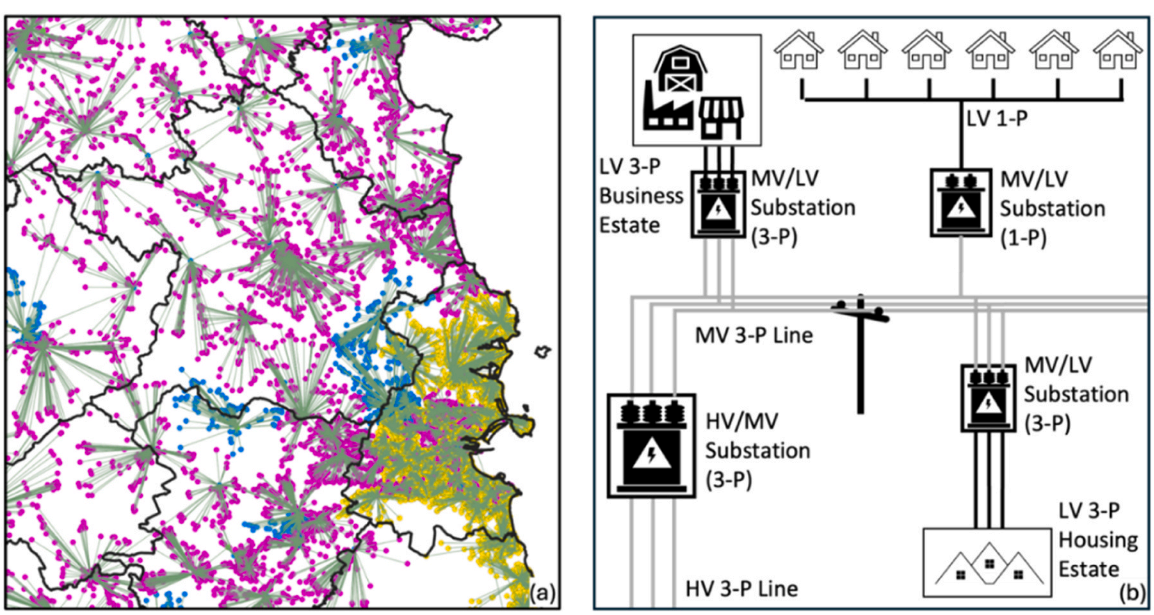

Fig. 2. (a) Grid hierarchy map for Co. Meath computed from ESB Network's Availability Capacity Map, illustrating substation locations, hierarchy levels, and hierarchy connections. **(b)** Schematics of power line connections for a rural cluster of houses, a housing estate, and a small business estate with single phase (1-P) and 3-phase (3-P) connections.

transformers are used for rural cluster connections with 50–200 kVA reserved for housing estates or farms/small business/ industry. Most rural clusters consist of groups from one to six houses and are fed using a single phase tap off the line to line of the MV feeder.

The distribution system operator (DSO), ESB Networks, designs the distribution grid to comply with European standard EN 50160 which states that each customer should receive between + -10% of the declared supply voltage of 230 V for 95% of the operating time [24]. This determines the maximum lengths of the MV and LV lines. Small excursions beyond this are acceptable, however, prolonged over-/ or under-voltage can result in damage to the customers appliances or the network itself. Many modern appliances can tolerate drops up to 10% of the base voltage but may switch off above or below that to protect the device.

3.2. Evolving load profiles

In designing a distribution grid and deciding how many customers to connect to a transformer of a certain size, grid providers rely on load diversity – the fact that loads are probabilistic and unlikely to switch on and off simultaneously. This concept is essential when developing cost effective infrastructure without having to oversize and overspend on grid assets. The degree of diversity in a cluster of houses is given by the Diversity Factor (*DF*). It is calculated over a time *t* as the sum of the individual maxima of customer loads during that time divided by the simultaneous maximum demand during *t* as:

$$DF = \frac{\sum_{n=1}^{N} \max(P_n)}{\text{maximum simultaneous load}(t)} \tag{1}$$

where P_n are the individual customer loads and *t* is the time period [25]. In a rural setting using conventional loads (No EVs, heat pumps, or distributed generation) diversity factors can lie upwards of 5. If the loads are more concurrent, the denominator increases, lowering the DF and resulting in a less diversified system. The After Diversity Maximum Demand (ADMD) and Maximum Demand (MD) as similar metrices commonly used by DSOs to size transformers for a given number of customers and can be calculated as:

$$ADMD = \lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} P_n(t) \tag{2}$$

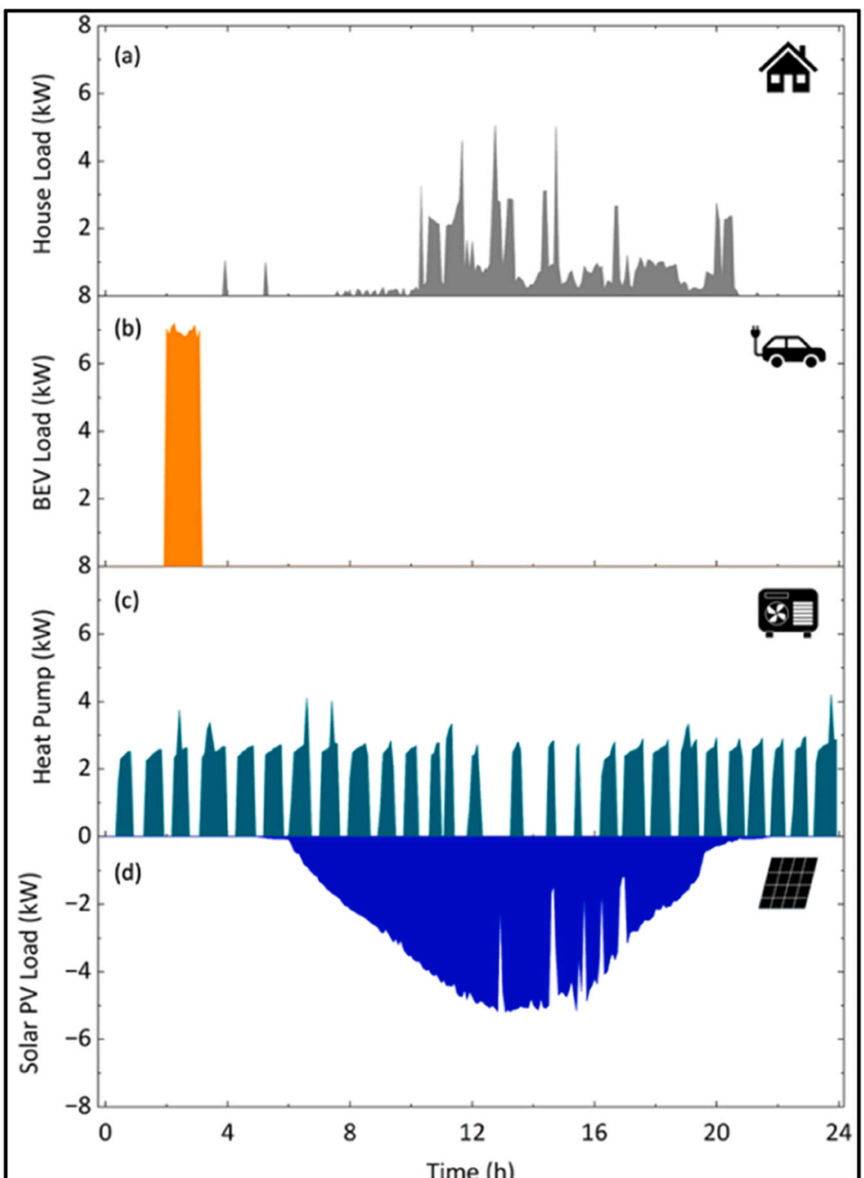

Fig. 3. Electrical load profile over one day of **(a)** rural home, **(b)** battery electric vehicle, **(c)** heat pump during winter use and **(d)** solar generation in summer.

$$MD = N \, x \, DF \, x \, ADMD \tag{3}$$

where P_n is the load of customer n at the time t of the highest coincident load peak of N customers [26].

The ADMD is the maximum simultaneous demand divided by the number of customers. The MD is then calculated as the product of customers N, the diversity factor and the ADMD.

The electrical load profile of a single residential customer contains sporadic jumps and spikes related to the switching of individual appliances. Increasing electricity demand in the past 30 years has largely been offset by improved energy ratings of devices and LED lighting, which means that the original sizing of the distribution grid did not urgently require an update. A 15 kVA pole-mounted transformer that accommodated six homes in 1980, assuming an ADMD of 2.5 kVA per house, could still accommodate those in 2010 and many grid assets are well exceeding their nominal lifetime [27]. However, with the introduction of new low-carbon technologies (LCT), there have been noticeable changes in consumer behaviour. The most relevant of those technologies are EV chargers, heat pumps and solar PV installations. Fig. 3(a)-(d) illustrate the different simulated load profiles for a conventional residential house, a BEV, a heat pump, and a 5 kW peak solar PV distributed generation respectively. The BEV, in this case, is drawing around 7 kW during night-time to avail of a low electricity price and for a period of one to two hours. This corresponds to around 32 A at 230 V. A heat-pump, depending on the model and the type of home, can draw around 2–3 kW in a cyclic pattern consistently during the day with higher loads in the winter months. Solar PV, as illustrated for a clear summer day and a 5kWp installation, mostly generates during mid-day and quickly exceeds typical household requirements in the Summer. This electricity must then be exported to the grid, which is shown as negative in the plot, and poses similar issues to local infrastructure as a load drawing high current.

We can see that these new appliances present significantly different load profiles and long continuous periods of high-power, which leads to significantly reduced diversity. This is recognised by ESB Networks who increased the ADMD per house from 2.5 kVA to 5.5 kVA in 2019. Where six houses could be supplied by a 15 kVA transformer before, the new minimum size is now 33 kVA. Although the challenges with 15 kVA transformers under increasing uptake of LCTs, particularly EVs, have been acknowledged by utilities and the regulator, the current approach remains largely reactive. Reinforcements are often initiated only after capacity issues are reported, assessed, and approved [28].

3.3. Plans for infrastructure improvements

The guidelines for how the DSO invests in grid infrastructure and related operations are set through price reviews (PR) from the commission for regulation of utilities (CRU). Despite being the most extensive element of the distribution system, the LV network has undergone the least amount of planned development over previous Price Review periods. PR5 covered the period of 2021–2025 and granted non-load-related capital expenditure (CAPEX) for ESBN of €693.8 m, up €200 m from PR4, with €38.8 m for the rural LV network and €141.2 m for renewing medium-voltage (MV) overhead lines [29]. This allowance is doubled in the upcoming PR6 to a baseline of more than €1.4b, acknowledging increased requests explicitly from renewing rural networks [28]. On the load-related CAPEX, reinforcement allowance in PR6 is up almost €1.2bn from PR5, reflecting MV/LV improvements and 20 kV conversions. Those include upgrades of 10 kV lines and transitioning to 33 kVA distribution transformers [28]. As part of PR5 efforts to prepare the LV network for widespread LCT use did not progress as planned. ESBN cited several factors including the sporadic layout of the LV network (which often requires bespoke design solutions), the disruptive nature of the work (which can involve civil works on private property), and the lack of data on LCT uptake [PR6]. Considering these issues, they adapted a reactive approach only dealing with new connection requests and voltage issues as they were reported. It is clear however that continuous investment in the LV network is required to facilitate the uptake of low carbon technologies including EVs and a much more proactive approach will be needed to ensure that we can meet our decarbonisation targets.

4. Spatial overlap of EV adoption and LV network constraints in Ireland

Identifying regions that are most likely to experience stress from mass BEV uptake over the coming years is important to prioritise proactive upgrades. This requires a spatial analysis of the current BEV distribution, expected BEV growth, as well as grid capacity availability. In this work, data from the Department of Transport (DoT), SEAI, and the Central Statistics Office (CSO) were consolidated to study EV distribution across Ireland. With their *Bulletin of Vehicle and Driver Statistics*, the DoT published a detailed breakdown of the entire vehicle fleet size in Ireland as of 2022. The SEAI publishes information on the spatial distribution of awarded grants for EVs and the CSO publishes information on the number of new car registrations. In combination, these sources allow an evaluation of the number of EVs and where they are bought and registered across Ireland. This is used to map current EV distribution (Fig. 4a) and regions of high EV uptake (Fig. 4b). ESBN publish a capacity availability heatmap, which contains a list of over 46,000 substations with information on location, transformer configuration and available capacity. This was used to visually analyse and evaluate the structure and capacity of the Irish distribution grid and identify constrained areas [30]. Clusters were formed working down from a transmission network connecting substation through the associated child substations. The visual analysis of geographic distributions of EVs and distribution grid structures was performed with QGIS using shapefiles provided by Tailte Éireann, Ireland's national land and property mapping authority and displayed in Fig. 4(c).

The term EV in the context of CAP targets applies to any vehicle with the capability of being charged electrically. This includes BEVs and PHEVs but excludes hybrid electric vehicles (HEV) which have no ability to be charged externally. Accurate information about the composition of the private car fleet is difficult to obtain and has last been published by the DoT in the Irish Bulletin of Vehicle and Driver Statistics. By December 31, 2022, the total number of BEVs is 36,000 (1.6%), with 33,000 PHEVs (1.5%) and 106,000 petrol or diesel hybrid electric vehicles (5%). Total fleet size of private cars was 2.255 million vehicles. Most BEVs recorded by the DoT were licensed in Co. Dublin and Co. Cork. Datasets published by the CSO show how the total EV share increased from 1.3% of new registrations in 2015 to almost 35% by 2024 with the majority being HEVs (16%) and BEVs (11.6%) and PHEVs only playing a minor role (7%). For 2021 to June 2025, CSO data shows almost 77,000 new BEVs registered with a peak in 2023 at 22,500 cars. Most new registrations were in Co. Dublin (45%), Co. Cork (10%), and Co. Kildare (6%). Combining data from the 2022 census and fleet information from the DoT, the distribution of BEVs per 1000 people per county can be mapped (Fig. 4(a)) [6,31]. Current penetration levels are low throughout the country but concentrate in and around urban centres. The number of BEVs per 1000 people is highest in Co. Wicklow (10.9), followed by counties Dublin (10.2), Kildare (8.8) and Meath (7.8). Fig. 4(b) illustrates the percentage growth in new BEV registrations between 2021 and 2024 [32].The highest growth rates of new registrations are seen in counties Monaghan (170%), Waterford (167%) and Meath (135%) highlighting the importance of more rural regions and especially those surrounding Dublin [3]. Since all PHEVs and BEVs require additional electrical capacity for charging it is relevant to compare EV distribution with the current electrical available demand capacity. Using ESB Network's *Availability Capacity Heatmap* [30], Fig. 4 (c) visualizes the demand capacity available per electoral division by assigning substation capacity to the electoral division in which it is

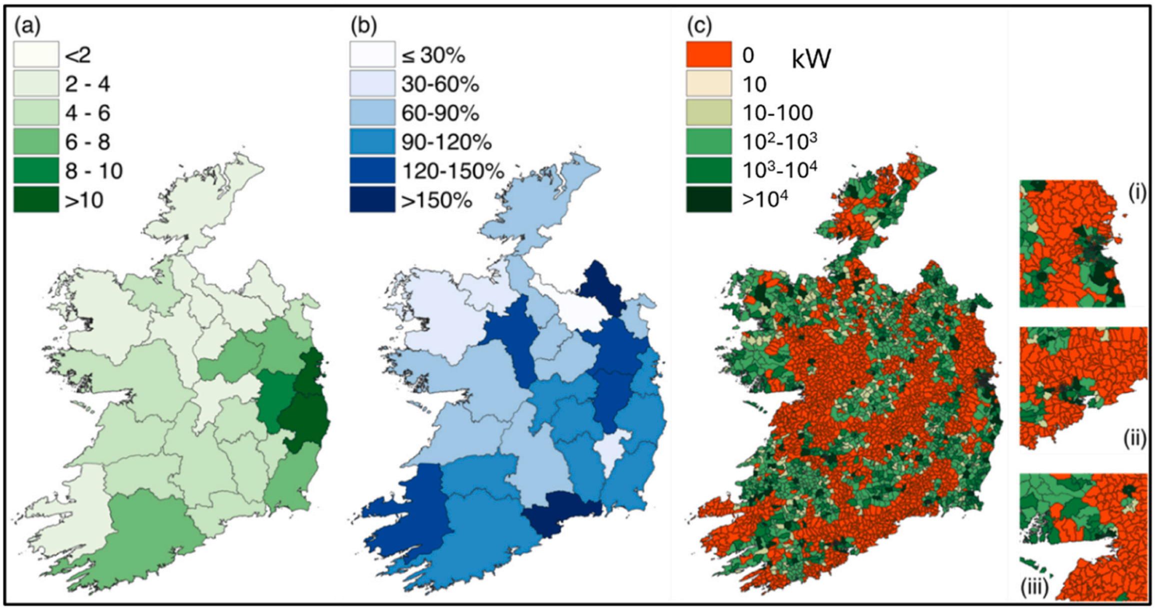

Fig. 4. (a) Current distribution of BEVs per 1000 people per county. **(b)** Change of new BEV registrations 2021–2024 (%) per county. **(c)** Available logarithmic demand capacity per electoral division computed from ESB availability capacity map with insets on Dublin (i), Cork (ii), and Galway (iii).

located. Following the hierarchical structure of the grid, the capacity of child substations is deducted from the available demand capacity of a parent station to avoid counting the same capacity as being available twice. The colour map in Fig. 4(c) represents logarithmic available demand capacity in kW. Red areas are effectively at capacity and have no space for additional connections. This is particularly relevant as Fig. 4(c) reveals more significant constraints in demand availability in those same sub-urban and rural regions which likely have experienced population growth in recent years and correspond with the regions with fastest increase in BEV uptake in Fig. 4(b). Urban centres, mainly Dublin, but also Cork and Galway, seem to experience significantly less constraints in demand capacity than the regions and electoral divisions surrounding them Fig. 4(c) (i)-(iii). This capacity map is particularly constrained due to the recent increase in ADMD assigned to each load from 2.5 to 5.5 kVA. A total of 26,168 substations, which represents 56.8% of all listed substations, experience constraints due to the parent capacity being limited but would otherwise have spare capacity for additional load [30]. This theoretical additional capacity amounts to 711.547 MVA of capacity that currently cannot be used [33]. As such ESBN is prioritising additional HV/MV substations, however as we discuss in this work there will still be significant upgrades required at MV/LV level.

5. Case study: rural cluster with six family homes

An electrical model was built to calculate the quasi-static current flow in a single-phase MV/LV transformer for a case of a six-home rural cluster under different load conditions using *PowerWorld* simulator. Six homes were chosen as representing the maximum number of houses to be connected to the new minimum transformer capacity of 33 kVA under an ADMD of 5.5 kVA per house. The model allowed us to vary the penetration of BEVs in that cluster and understand the resulting impact on the local transformer and the voltage regulation, solving for the current and voltage at each node (bus) and through the transformer. To solve the power flow, PowerWorld simulator relies on the Newton-Raphson algorithm to solve the nonlinear equations of the power system based on input parameters and system configuration (see

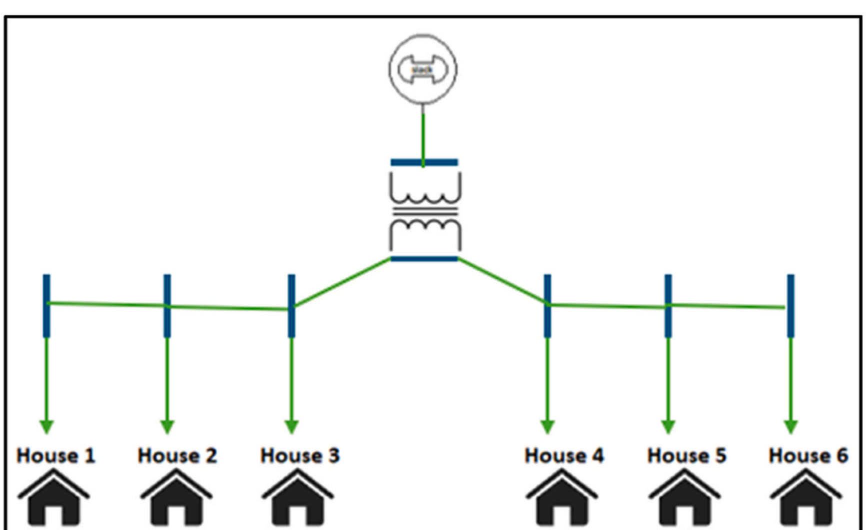

Fig. 5. Powerworld simulator one-line diagram with a MV/LV transformer between six homes.

supplemental section A) [34]. The transformer is connected in such a way that on the LV side it splits the cluster with 3 houses to either side (Fig. 5). A 20 kV slack generator is used to simulate the MV side connected to the primary side. For each house, a load profile of power consumption was uploaded for a three-day period in 5-minute intervals.

While the ADMD has been increased and 33 kVA is the new minimum transformer size, 15 kVA transformers are still relevant in the present grid layout [35]. Therefore, the parametric analysis explored transformer capacities ranging from 15 kVA to 100 kVA. In rural Ireland, pole mounted transformers and overhead lines are a common way of installation, allowing relatively easy access over underground infrastructure as well as enhanced air-cooling but also higher susceptibility to damage from weather events or other accidents [23]. The windings in these MV/LV transformers are typically sheets of copper for the higher voltage side and sheets of aluminium for the lower voltage side, wrapped around a steel core and insulated with sheets of paper in between the layers. This structure is then immersed in mineral oil which acts as a dielectric insulating material and a coolant to transfer excess thermal energy from the core and the coils to the surface of the transformer [36,37]. Small pole-mounted transformers rely on natural convection for the cooling process and natural air convection to remove heat from the external surface, while larger transformers are equipped with more active cooling mechanisms. This work evaluates the thermal behaviour of oil-natural air natural (ONAN) transformers with natural convection for cooling.

Transformers have an internal impedance due to the winding and core losses which lead to real and reactive power loss. This can increase the current and reduce the voltage on the secondary side when the transformer is run close to its nameplate value. For a 15 kVA transformer supplying 65 A at 230 V on the LV side, the losses can lead to heating rates above 500 W, and the resistive heating can result in a fast temperature rise of the coil, also known as hot-spot (HS) temperature, followed by slower response of the oil temperature. ONAN pole-mounted transformers are designed to operate with a maximum HS temperature of 110°C under continuous load with a normal life expectancy of 20.55 years

Modern overhead LV lines are aerial bundled cables (ABC) with cross-linked polyethylene insulation and typically 2-core, live and neutral. Each cable, or conductor, has a cross-sectional area of 35–95 mm^2. Older cables might be even thinner, 16 mm^2 or 25 mm^2, which leads to significantly shorter acceptable runs because of higher cable impedance in smaller cores. For the model LV cabling 35 mm^2 ABC is chosen as an acceptable reference value for the model with an impedance of 0.87Ω/km and 100 m [38]. The measured current profiles for different load cases were then converted to temperature profiles in the transformer using a simple thermal RC model. The thermal model is a standards-based two-branch framework from IEC 60076–7 [39] and IEEE C57.91 [40]. Specific details of the model and parameters used are outlined in the supplemental section A. Using the simulation and the thermal model allowed us to adequately size the transformer and identify any reduction in transformer operational lifetime due to overheating.

5.1. Load profile analysis

For this work, conventional electrical load profiles were recorded at 5-minute intervals at a rural single-family detached house in Co. Meath and served as a baseline consumption to model the impact of BEV charging on top of domestic load curves. Energy use was about 12kWh/day which is in line with averages for rural areas. There are currently no suitable datasets on domestic charging profiles of BEVs in Ireland, so a set of synthetic profiles has been developed based on trip data, power consumption data and technical specifications from available home chargers and cars. According to the *National Household Travel Survey 2023*, conducted and published by the NTA the average trip distance in rural areas is 16.70 km with an average daily trip rate of 2.55 trips per day. The share of trips taken by car is 82% [9]. Accounting for this share, the total distance travelled by car each day can be approximated as 35 km which we used in this study.

Typical power consumption of BEVs varies depending on the model. For the Tesla Model 3, power consumption is listed with 13.2kWh/100 km in the base version whereas the Volkswagen ID.4 lists 16.5kWh/100 km and the Kia EV6 has 16.4kWh/100 km representing three out of the five top selling BEVs in Ireland in 2024 [41–44]. Real data measured at a rural house in Co. Meath indicated a daily trip data of around 60 km and a power consumption of 20kWh indicating that the ideal driving behaviour assumed by manufacturer's does not hold under real-world conditions and motorway driving. To derive synthetic EV charging profiles for the simulation, an average daily trip distance of 35 km at 18kWh/100 km is assumed, amounting to 6.3kWh of power per day per car. To allow for day-to-day variability in driving patterns, a standard deviation of 1.5kWh is assigned to the daily power consumption. Single-phase AC chargers, listed in ESB Networks' low carbon technology register are rated at 7.36 kW [45]. Accounting for losses and variability in the charging process and taking into consideration a real-world charging profile, the power drawn by a home charging unit in the model is set to 6.8 kW with a standard deviation of 0.15 kW and limited to stay between 6.5 kW and 7.1 kW. For the charging profiles, the charging window was set between 02:00 and 04:00 to reflect current Irish electricity tariffs that financially incentivize night-time charging within defined off-peak windows. While these windows may evolve and real-world charging behaviour is likely to be more heterogeneous, including workplace or public charging and varying start times, this study intentionally focuses on concentrated home charging to evaluate potential worst-case impacts on rural LV networks under limited flexibility. A detailed sensitivity analysis of charging behaviour and tariff evolution in future work, could provide valuable insight into the generalization of these findings. The parameters for generating the synthetic BEV load profiles are summarized in Table 1. The python code for generating the profiles is provided in the supplemental information section B.

In practice, BEV drivers might choose to charge using public infrastructure or deviating time windows occasionally. Nevertheless, assuming uniform night-time charging is a reasonable basis to assess the distribution grid's ability to accommodate the additional uncoordinated and therefore simultaneous loads from BEVs. Regulation in the UK mandates charge points to follow a randomised delay of up to 10 min at each charging instance to avoid a high number of charging events starting simultaneously and causing sudden spikes or drops in the distribution grid [46]. This is reflected in the synthetic load profiles through a randomized start time between 2:00 am and 2:15 am. It is assumed that each of the six houses installs a charger sequentially, first running one battery electric vehicle per premises and then converting to 2 BEVs at each premises as the penetration surpasses 50%. This may not be an entirely realistic assumption as it is likely that early adopters could move to two BEVs before other households have one, but it is a reasonable approximation to simplify the analysis for the purpose of this work. The resulting charging scenarios for different EV penetration cases are shown for 1,4,8,and 12 EVs in Fig. 6 below.

Because of assumptions regarding EV charging behaviour during night-time, the peak load of around 41 kW is reached at one BEV per home and stretches for a longer period as BEVs are added afterwards as

Table 1
Input parameters for generating synthetic BEV load profiles.

BEV synthetic load profile input parameters	
Distance travelled/car/day	35 km
Energy efficiency	18kWh/100 km
Energy /car/day	6.3 + -1.5 kWh
Charging rate	6.8 + -0.15 kW
Start time window	02:00 am – 04:00 am

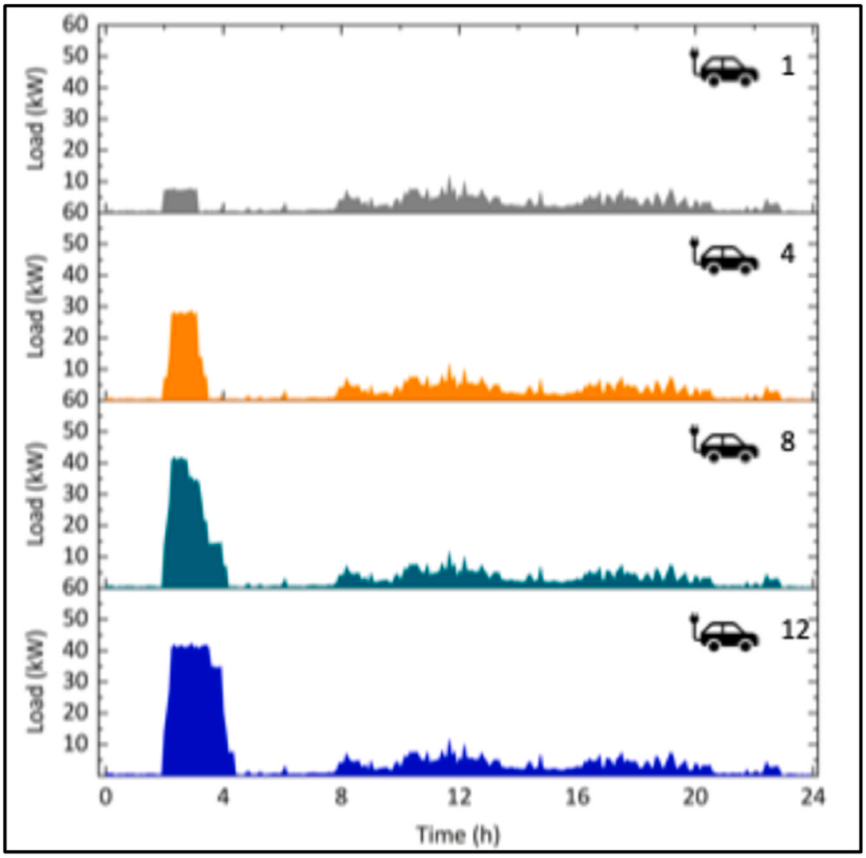

Fig. 6. Cumulated load profile of six houses with different numbers of EVS over a 24 h period.

we assume a single home cannot simultaneously charge 2 EVs. A summary of the load statistics for scenarios with different BEV uptake is shown in Table 3. The DF decreases from 2.49 to 1.05 as the number of EVs increases and the probability for simultaneous charging and a higher simultaneous peak demand becomes higher. The ADMD therefore also increases from 1.9 kW per customer without EVs, to 7.1 kW per customer at higher shares of BEVs. This then corresponds with much larger transformer sizes required to accommodate the additional loads where the ideal transformer size is selected from capacities of transformers presently deployed in Ireland. The kwh/day demand is also shown to increase significantly showing that along with infrastructure upgrades significant new generation will need to be brought online to support electrification of transport.

5.2. Line impedance and voltage droop

Next, we look at the impact of the new load profiles to the local voltage and current on the LV lines. The LV line impedance means that for larger current draws associated with EV charging the customer can expect to see a reduction in supplied voltage. This is the more significant the further away a customer is stationed from the distribution transformer. The results of voltage output of the transformer and voltage received at each of the six premises, measured at the respective buses in the simulation and over a simulation period of 24 h is presented in Fig. 7 with a 33 kVA transformer and 100 m of 35 mm^2 ABC conductors between the houses.

In a 230 V single-phase network, the negative voltage deviations are seen to remain within the 10% limit of 23 V and above 207 V in total during the regular loads without EV charging. At peak times during six simultaneous EV charging events, however, voltage drops significantly to below 205 V. This is most severe for houses 1 and 6, which have the longest distance between themselves and the transformer, marking line distance as a major issue during high concurrent loads or with older and more resistive powerlines. Regarding EV home chargers, they are typically equipped with voltage detectors which continuously monitor the utilization voltage at the charger. If voltage levels fall outside the 207 V to 253 V range, the charger disconnects for safety reasons, so for properties already operating near the lower supply limit, even a modest

Table 3
Diversity, energy demand and capacity across the six-house cluster under different BEV uptake scenarios.

Case (BEV Share)	DF	ADMD [kW/house]	Peak simultaneous demand [kW]	Ideal transformer capacity [kVA]	Total energy demand [kWh/d]
No EV (0%)	2.49	1.90	11.7	15	59.1
1 EV (8%)	2.67	1.95	11.7	15	67.2
2 EV (16%)	2.33	2.47	14.8	15 or 25	73.6
4 EV (33%)	1.35	4.80	28.8	33	89.9
6 EV (50%)	1.05	7.10	42.5	50	103.4
8 EV (66%)	1.08	7.10	42.5	50	115.8
12 EV (100%)	1.08	7.10	42.6	50	137.2

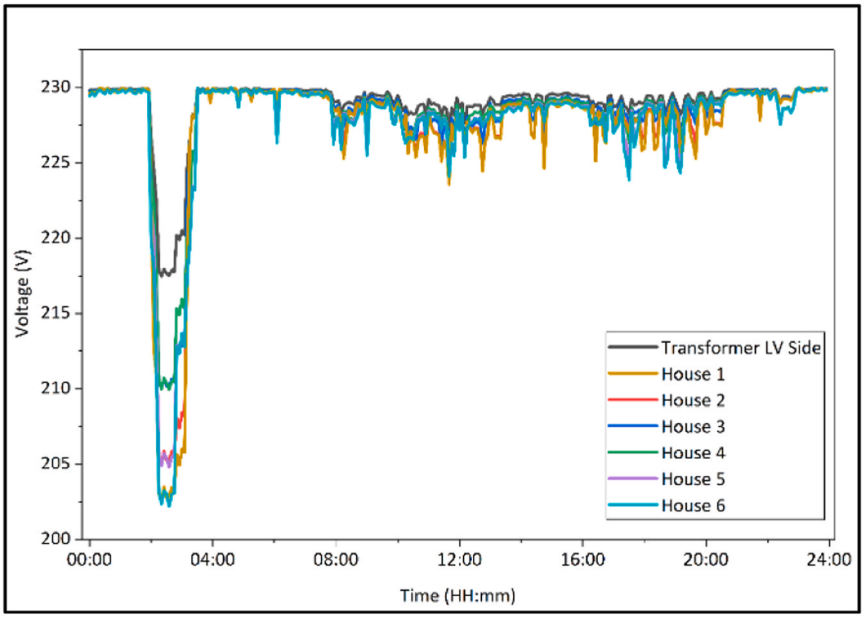

Fig. 7. Voltage level at the transformer and each house from the six-house cluster during a 24 h period with six BEVs and fed from 33 kVA transformer.

voltage drop can cause the utilization voltage to dip below 207 V, resulting in the charger shutting down. The tripping out of EV chargers due to under-voltages can be an issue causing frustration, hindering uptake and potentially also damaging charger, vehicle or grid stability. In addition to load-driven voltage drops, reverse power flow from distributed PV installations can cause voltage rises along resistive LV feeders. In rural clusters, PV generation typically peaks around mid-day when domestic demand is low (Fig. 3), resulting in net export toward the transformer and a voltage increase proportional to feeder impedance on exported active power. While ESB Networks permits simplified single-phase microgeneration connections up to 6 kWp, practical export capacity in rural networks may be as low as 3kWp where voltage rise limits are binding, highlighting the bidirectional stress placed on LV infrastructure as both EV charging and PV penetration increase [35].

5.3. Thermal response of LV transformer to increasing BEV uptake

The electrical model solves for the current flow in the MV/LV transformer which can then be related to temperature rise using the simple RC model. Because winding losses scale with the square of load current relatively small increases in current can have a large impact on transformer temperature. Using the thermal model and the parameters described in the supplemental section A, hot-spot and top-oil temperature can be derived for different transformers under different load scenarios. Higher capacity transformers, which have thicker windings, lower resistance and larger oil volumes, show slower temperature increases and lower maximum temperature under a given load. This is expected and positions higher capacity transformers as reasonable substitutes for 15 kVA transformers that experience too much stress under increased loads from LCTs and particularly BEV uptake in rural clusters. Top-oil and HS temperatures are computed for different combinations of BEV uptake and transformer capacity, ranging between no BEVs at a 15 kVA transformer to 12 BEVs or 100% BEV uptake at a 100 kVA transformer over a three-day period, shown in Fig. 8.

The temperature curves illustrate that night-time overlapping charging of BEVs has a significant impact on the temperature profile of the local distribution transformer. Adding only one BEV to the cluster, can raise temperatures to similar levels as under combined consumption before and without EVs. At 2 BEVs and simultaneous charging at night, the temperatures reach close to the limits of 110°C for the 15 kVA transformer, which is expected given that each EV is set to charge at around 6.8 kW. For further simulations, the transformer size is increased, as adding more BEVs would exceed the temperatures of the 15 kVA transformer by an extent that would require a replacement as in Fig. 8(d). A 25 kVA transformer could be capable of dealing with up to 4 BEVs charging simultaneously and a 33 kVA performs well at BEV uptake of around 66% or 8 cars in total (Fig. 8(f)). 100% BEV uptake, towards reaching the net-zero goal for 2050, would then require a 50 kVA transformer for the examined six-house rural cluster under the defined parameters (Fig. 8(g)). This is under the assumption, that charging is limited to one car at a time per household and that a household with more than one EV would charge sequentially, effectively increasing the charging time per house. Longer charge times impact transformer temperatures as they prolong the time during which the transformer and mainly the mineral oil heat up and they increase the likelihood and duration of simultaneous charging events in the cluster.

What is also notable about the temperature curves in Fig. 8, is the large daily temperature excursions that are caused by night-time charging. Even if adequate transformer sizing can keep temperatures below the rated maximum, the increased temperature cycling will likely affect transformer aging and longevity. Currently, distribution transformers often exceed their average 20-year lifespan, supported by long periods where temperatures remain below maximum values. However, the introduction of BEVs, as seen in Fig. 8, can introduce significant shifts in transformer loading, unseen in previous decades and the extent of their impact on transformer ageing will need further long-term or accelerated aging tests as the network evolves. Table 5 summarises key parameters for each of the observed cases, including maximum currents, maximum temperature change and maximum HS temperatures.

5.4. Additional impact of solar PV and heat pump uptake

The Irish government is also setting targets for the electrification of heating and the deployment of distributed small-scale direct generation through solar PV. Particularly, new residential buildings from 2021 onwards must comply with the *Nearly Zero Energy Building* standard, typically matching a building energy rating (BER) of A2, which is the second most-efficient level after a BER of A1 [47]. As such, many new projects deploy air sourced heat pump and solar PV technologies as standard. For solar PV, the typical upper limit of maximum export

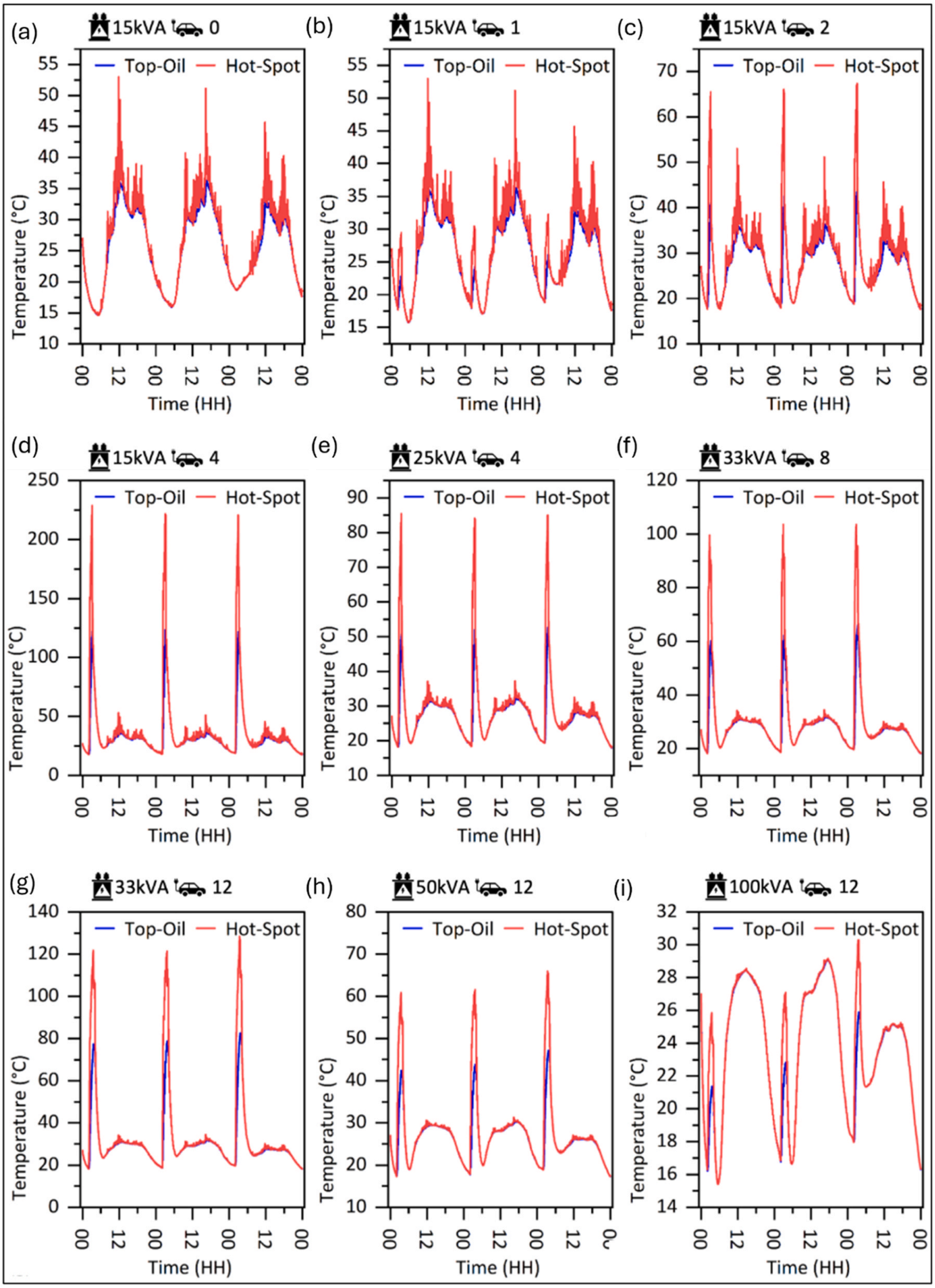

Fig. 8. Thermal response of oil and hot-spot temperatures in different transformer sizes and for different numbers of BEVs across six houses and a three-day period.

capacity (MEC) is 6 kVA or up to 25 A at 230 V for a single-phase connection [48]. SEAI grants for solar PV support an installation of up to 4kWp, which is well below the MEC defined by ESB Networks [49]. Larger PV arrays could be installed and support self-consumption but would not be allowed to export above the MEC. For heat pumps, the target as formulated in CAP 24 is to have 680,00 heat pumps deployed by 2030 which would consist of 280,000 new builds and 400,000 retrofits. The solar PV target is to have 2.5 GW new non-utility generation capacity by 2030 [3]. Electricity generated from solar PV, if matched with coincident demand behind the transformer, that is another house in the same cluster can consume this generated electricity, does not necessarily have to go through the transformer and into the MV grid. In

Table 5
Summary of the results from the electrical/thermal model for different scenarios of BEV uptake and transformer capacities in the six-house cluster.

Case (BEV share)	Capacity [kVA] (ideal)/case	Pmax [kVA]	Imax [A]	T_{HS} max [°C]	ΔT_{HS} max [K]
No EV (0%)	(15) / 15	12.2	52.9	53.0	17.8
1 BEV (8%)	(15) / 15	12.2	52.9	53.0	17.8
2 BEV (16%)	(15) / 15	15.9	69.1	67.3	29.0
4 BEV (33%)	(33) / 15	32.7	142.2	228.7	117.2
4 BEV (33%)	(33) / 25	31.1	135.2	85.5	38.3
6 BEV (50%)	(50) / 33	47.6	207.1	103.6	50.0
8 BEV (66%)	(50) / 33	47.6	207.1	103.6	50.0
12 BEV (100%)	(50) / 33	47.6	207.1	128.4	50.0
12 BEV (100%)	(50) / 50	46.6	202.5	66.0	20.7
12 BEV (100%)	(50) / 100	45.6	198.3	30.3	5.0

this case, there would be no effect or interaction with the transformer at all. However, in reality, solar PV generation on a sunny day quickly exceeds demands and especially in a setting of high PV penetration leads to increased exports of electricity during the day. To discuss the combined impact of these LCTs and the increased load due to home charging of BEVs, a representative case for 2030 was simulated in Powerworld in the same six home cluster as before. In this scenario, there are 6 homes with 4 BEVs, 2 heat pump installations and 2 5kWp solar PV installations. The resulting current draw from the transformer is shown in Fig. 9(a). The loads were evaluated for a 72-hour period in mid-Summer with high expected solar PV output and low demand from heat pumps and for a 72-hour period in Winter, where solar PV output is negligible, but heat pump demand is high. Solar generation curves were recorded at the same location as the consumption profiles in Co. Meath for a 5kWp installation. Heat pump load profiles are taken from a dataset on heat pump monitoring in the UK for a period between 2013 and 2015 and available from the UK Data Service [50]. The dataset consists of 697 air-sourced and ground-sourced heat pump installations. Six profiles were selected from a total of 106 heat pumps in domestic and detached houses. For each profile, three consecutive days from January 2014 were taken as input data for load profile modelling to reflect maximum expected heat pump loads in testing grid capacities.

Ambient temperature data is available from Met Éireann, the Irish meteorological service, for the Dunsany station in Co. Meath, and three consecutive days have been selected for the winter (26/01–28/01), average (17/05–19/05), and summer (08/07–10/07) as reference temperatures for simulation [51]. Fig. 9(a) shows the total current draw for this case in Winter (black) and Summer (red).

We can see that the correlated night-time BEV charging is still the dominating factor for transformer current draw and transformer top-oil and HS temperatures (Fig. 9(b) and Fig. 9(c)). Intuitively, it could be assumed that high solar generation would offset the increased load from BEV adoption, but due to the time mismatch, this is not the case. To achieve this effect, small-scale storage solutions would have to be installed at the premises or by the transformer to store excess electricity from solar PV for later use. Nevertheless, because of current market structures and the day-night variability in electricity prices, consumers are incentivized to sell generated electricity during the day and import electricity from the grid at night. Heat pumps, while not relevant during summer, could cause problems in winter depending on the type of heat pump that is installed as it could overlap with charging periods at night and potentially overstress the transformer and generate critical voltage drops.

5.5. *Importance of smart chargers*

Smart charging in the context of this work refers to BEV home chargers which can either be controlled by the grid operator or communicate with other EV chargers locally to coordinate charging times. Smart features commonly also include static scheduled charging to avail of smart EV tariffs, dynamic price-based charging, grid responsive charging and local feeder balancing. Most users would typically plug-in their BEV overnight and require a certain charge by morning and they may have some flexibility regarding when exactly the car is charged. Smart enabled chargers are now mandatory for new installs in the UK and have moved from pilot phase to real world applications. For example in high density urban areas such as apartment blocks and car parks [46] smart charging is essential to distribute the available capacity amongst various users. In the case of a rural cluster of homes in Ireland, smart EV chargers could communicate within the cluster, in principle allowing to organise in such a way that multiple simultaneous charging events can be avoided which lead the grid-critical situations. In this work, the effect of smart charging is very simply simulated by diversifying the charging time between individual customers. Under a smart charging regime, it is assumed that electricity providers extend their night-time window to between 11 pm and 8 am to enable a better distribution of charging events. The algorithm used is

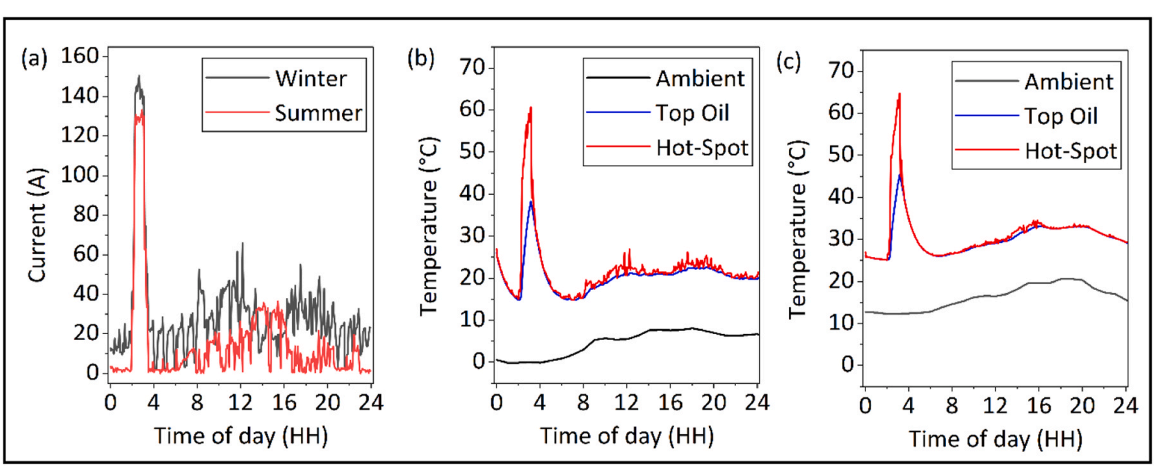

Fig. 9. (a) Current draw under 2030 scenario, (four BEVS, two heat pumps and two 5kWp Solar PV installations) in summer (black line) and winter (red line) using under a 33 kVA transformer. (b) Transformer oil and hot-spot winding temperatures of winter case with high heat pump demand and no solar generation. (c) Temperature profile of a summer case with high solar PV generation and no heat pump loads.

outlined in the supplemental information section D. It looks at the individual charging profile and shifts it to a slot where it least overlaps with other profiles thereby reducing peaks in total demand per night without changing duration and amount of charging for any profile. Fig. 10(a) shows the current profile for the case of 6 BEVs (one per household) with (green line) and without (red line) smart charging, with Fig. 10(b) showing the resulting top-oil and HS temperatures for smart and non-smart charging profiles. Fig. 10(c) shows the case of 100% EV uptake with and without smart charging, with Fig10d showing the resulting temperature profiles.

Given the same usage case as studied before, smart charging can almost completely remove the immediate need for transformer upgrades, allowing existing 15 kVA transformer standards to be used, as effectively only one EV is charging at any one time. Still, because smart charging is not yet widely deployed in Ireland and consumer incentivisation remains unresolved, LV grid reinforcements will still be required. Especially with additional loads from solar PV and heat pumps expected to become more relevant in coming years. Smart charging and demand-side flexibility are, however, promising measures to reduce additional capacity requirements and to support overall grid stability.

5.6. Limitations

The case study is based on a single six-house rural cluster, representative of Irish LV networks. While the chosen configuration reflects common rural feeder characteristics, results may not directly generalize to urban feeders, meshed networks, or systems with different transformer sizing and voltage regulation practices. Charging behaviour was modelled using a concentrated night-time window consistent with current Irish tariff incentives and assumed charging powers between 6.5 kW and 7.1 kW. This approach intentionally represents a structured home-charging scenario but may not fully capture potential future behavioural diversity, such as wider tariff windows, mixed start times, public or workplace charging or concurrent rather than subsequent multi-EV charging within a household. A broader sensitivity analysis incorporating behavioural heterogeneity of domestic loads beyond six homes, diverse EV charging patterns and alternative tariff scenarios could provide further insight into the robustness of the findings and necessity of grid reinforcements.

6. Conclusions

The adoption of EVs, and BEVs, in the Republic of Ireland has been studied, finding that rural areas and especially those surrounding dense urban centres have the fastest EV uptake and at the same time experience the most issues in terms of car dependency and electrical grid capacity constraints. These constraints can lead to negative user experiences when transitioning to EVs which could significantly impact continuing EV uptake and negatively affect transport decarbonisation in Ireland. Evaluating BEV impact on local rural distribution systems, it is found that changing domestic load profiles due to prolonged and simultaneous high-power draw from EV charging leads to elevated transformer temperatures, which can cause significant reductions in operational lifetime. This problem is expected to be amplified with increased penetration of solar PV during summer and heat pumps during winter and through power line impedance over longer distances.

Smart EV charging, such as an automated allocation algorithm to minimize simultaneous charging events during a prolonged period, can significantly reduce the temperature increase in a transformer during night-time charging thus improving operational lifetime. This flexibility potential of electric vehicles is an important characteristic which distinguishes it from solar PV and heat-pumps which tend to have highly correlated and less controllable grid requirements. To fully avail of this potential, requires harmonization of time-dependent electricity tariffs and common technological standards for charger communication. Additionally, consumers must be given an incentive to hand over control of charging their vehicle to a certain degree to a utility or electricity provider to coordinate with respect to local and regional grid constraints.

Given the proposed financial investment into reinforcements of the distribution network as part of PR6 by ESB Networks, the ambitious targets for EV penetration by 2030 and the trajectory of complete transport decarbonization, efficient upgrade processes are important. We show that rural residential clusters start experiencing current and

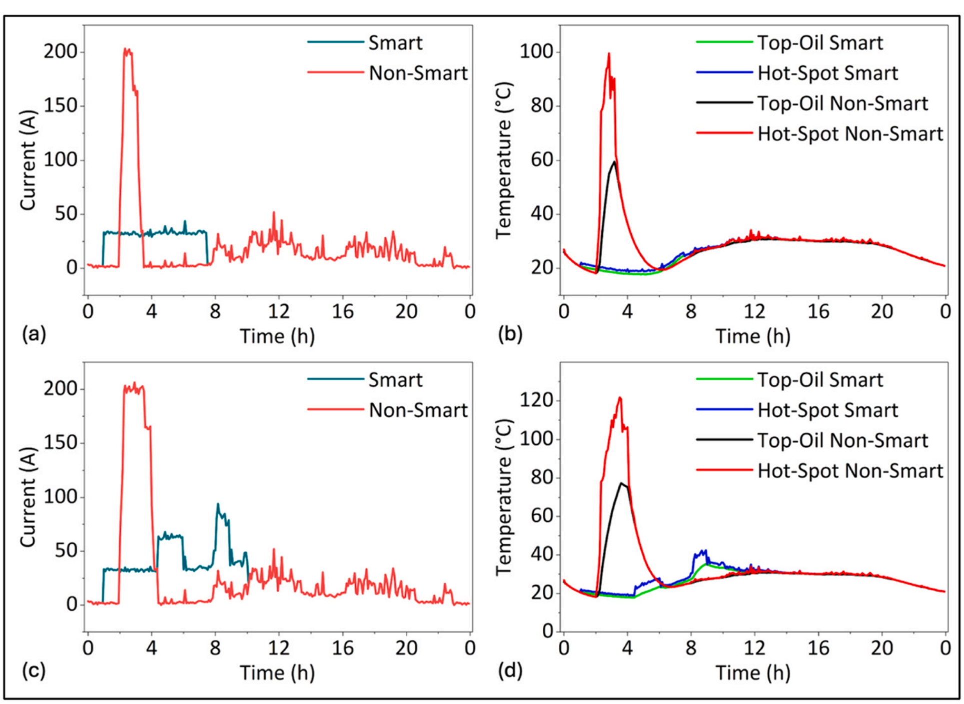

Fig. 10. Current **(a)** and hot-spot/top-oil temperature **(b)** profiles for a 33 kVA transformer for six houses with six BEVs. Current **(c)** and hot-spot/ top-oil temperature **(b)** profiles for a 33 kVA transformer for six houses with 12 BEVs.

voltage issues with just 2 BEVs adding to the combined load. ESB Networks is meeting additional demands with 33 kVA as their new minimum standard for distribution transformer sizes, but upgrades should be scheduled proactively, especially in rural areas, to enable widespread BEV uptake. A reactive approach can result in long lead times, potentially leaving customers with limited charging capacity or reduced supply reliability during the transition and thus affect reaching the transport decarbonization targets.

The widespread deployment of smart meter devices can facilitate a more accurate and geographically dispersed analysis on load profiles across urban, sub-urban, and rural Ireland with more granular information on expected loads from EVs, as well as heat pumps and solar PV generation. With their Smart Meter Data Access Code, the CRU is in a process to make data from over 1.9 million smart meters in Ireland available for analysis to improve network operation and explicitly working towards meeting climate action targets in a way that is compliant with data protections laws [52]. Access to such information would allow more accurate analysis of diversity factors in different settings and for varying combinations of customers which was limited in this work.

In this work we considered a case study of six residential premises connected to a pole mounted MV/LV transformer to illustrate some of the issues associated with electrification of transport in rural areas. While a full parametric sensitivity study regarding different charging behaviours was beyond the scope of this work, the increase in EV adoption could provide relevant evidence for realistic charging behaviour in rural Ireland contributing to the discussion of grid readiness and potential risks for LV networks. This case study, however, demonstrates the urgent need for rural infrastructure upgrades and further investigations, showcasing the impact the early adoption of smart charging could have on enabling our sustainable mobility transition. It also paves the way for future investigation of transient analysis, balancing of the three phase feeders, and capacity constraints at parent substations.

CRediT authorship contribution statement

Alexander Voß: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Abhilash C. Singh:** Writing – review & editing, Supervision, Methodology. **Caulfield Brian C.:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **McCloskey David:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.segan.2026.102209.

Data availability

Data will be made available on request.

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