Proceedings Paper:

McKinney, T.R., Ballantyne, E.E.F. orcid.org/0000-0003-4665-0941 and Stone, D.A. orcid.org/0000-0002-5770-3917 (2023) Investigating the impact of electricity rationing on rural EV charging. In: Muhammad-Sukki, F., Aini Bani, N. and Tingas, E.A., (eds.) Transportation Research Procedia. 8th International Electric Vehicle Conference (EVC 2023), 21-23 Jun 2023, Edinburgh, United Kingdom. Elsevier BV , pp. 61-68.

https://doi.org/10.1016/j.trpro.2023.11.002

Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 70 (2023) 61–68

Transportation Research Procedia

www.elsevier.com/locate/procedia

8th International Electric Vehicle Conference (EVC 2023)

Investigating the Impact of Electricity Rationing on Rural EV Charging

Thomas R. McKinney[a,*], Erica E. F. Ballantyne[a], David A. Stone[b]

[a] Sheffield University Management School, The University of Sheffield, Conduit Road, Sheffield S10 1FL, UK
[b] Department of Electronic and Electrical Engineering, The University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, UK

Abstract

The Electricity Supply Emergency Code (ESEC) outlines the process for electricity rationing via a range of scenarios (Levels 1 to 18), should a critical supply incident affect a specific region, or the whole of the UK. Given recent global events, the threat of its implementation is currently attracting large mainstream media attention and genuine concern. With the uptake of Electric Vehicles (EVs) increasing, motorists are ever more reliant on a resilient electrical grid in order to charge their vehicles. This paper is the first of its kind to consider the impact on the ability to charge EVs should the ESEC specifically be invoked. This paper also focuses on rural areas, in particular a small rural village in the UK, Bradbourne, located in the Peak District. For which a novel EV Charging Model has been designed to incorporate the patterns of various levels of disconnections as laid out in the ESEC. Additionally, two behavioural approaches to charging within a planned power outage have been modelled. Real concerns arise in the eventuality of the higher level scenarios being implemented, with almost 30% of modelled EVs unable to complete their planned journeys. Although peaks of grid demand are reduced, results in fact show very little energy reductions overall depending on the charging behaviour, thus rendering the efforts of the ESEC mute.

Keywords: Electric Vehicle; EV Charging; Electrical Grid; Power Cuts; Rural Transport

1. Introduction

Electric Vehicles (EVs) are becoming increasingly popular in recent years, due to their multiple environmental benefits and lower running costs [1]. Coinciding is the increased political pressures from the UK Government which

* Corresponding author.
E-mail address: trmckinney1@sheffield.ac.uk

10.1016/j.trpro.2023.11.002

hopes to accelerate the uptake of EVs from the current 400,000 (1% of total vehicles) on UK roads, to 23.2 million by 2032 (55% of total vehicles) (CCC 2020). A large part of this pressure comes from the UK Government's latest Ten Point Plan (Energy Saving Trust, 2021) which bans the sales of new cars with internal combustion engines from 2030 and new hybrid cars from 2035 (Groves and Pratt 2023).

A crucial aspect of this new energy vehicle transition which has received a lack of attention is the impact on the rural areas of the UK. Rural areas come with their own nuances impacting the smoothness of this transition. Larger journey distances/times (DEFRA, 2021) resulting in different travel patterns and thus different charging behaviours, combined with typically less robust grid infrastructure in general (i.e. smaller substations, or transformers, attached to wooden poles) (Western Power Distribution, 2022) all highlight the need for separate consideration from their urban counterparts; which are already experiencing increases in the installation of public charge points to support the EV future (DfT 2020). In contrast, a lack of consideration for rural areas has already seen them left behind from previous large-scale socio-techno transitions, such as increased internet speeds and mobile connectivity (Williams et al., 2016).

It is widely understood that large EV market penetration will lead to increased peak demand causing voltage violations, system losses and difficulty in optimising power grid operation control (Crozier et al., 2021; Wang et al., 2018). In this electrified vehicle future, a potential major cause of concern is the impact of power cuts, due to increasing numbers of motorists becoming dependent on an unfailing electrical grid to keep their vehicles operational. Although power cuts are an infrequent occurrence in the UK, natural disasters (i.e. storms and extreme weather) can still cause longer term power outages, particularly in more rural and remote locations. On the 9th of August 2019, a large scale power outage caused interruptions to over 1 million UK consumers' electricity supply (Ofgem, 2020). In addition to these unplanned power outage scenarios, recent global affairs have exposed the threat of energy generation difficulties in the UK. This has led to the UK Government considering invoking the Electricity Supply Emergency Code (ESEC) as mitigation, receiving large media attention (The Guardian, 2022). The ESEC outlines various levels of disconnection for households in order to ration the available energy during supply/generation issues. This paper aims to investigate the impact that implementation of the ESEC would have on electric vehicle users, in particular those in rural communities. The remainder of this paper is therefore organized as follows: the research approach, including a background literature review and how the papers scope fits in is presented in Section 2. Section 3 details the methodology employed followed by a presentation of the results and discussion in Section 4. Section 5 concludes the paper.

2. Research Approach

Multiple studies have shown the threat of large scale EV adoption in relation to causing grid failures (Wang et al., 2018; Clement-Nyns et al., 2010). Ashfaq et al. (2021) highlighted the largest threat coming from uncoordinated charging behaviour, as this would deteriorate the distribution system’s functioning (i.e. transformer overloading, voltage instability, power loss, and frequency variations), which may collapse the power system (Clement-Nyns et al., 2010; Martinenas et al., 2016).

Hartvigsson et al. (2022) conducted the first national coverage of EV charging impacts in residential areas for Sweden. Results showed that the risk of power system violations due to EV charging are greatest in cities and smaller in urban areas, while rural areas show significantly fewer violations. Although this comes down to the infrastructure in the area, if built to the same level as that in urban areas, as in Hartvigsson et al. (2022); since the number of customers in a low-voltage grid decreases, the designed grid capacity per customer increases and so reduces the likelihood of voltage violations to occur when adding EV charging loads. However, even pricing points from chargepoint operators could cause grid instabilities if charging rates are changed too quickly and the grid does not have the capabilities to respond fast enough to these changes (ADE 2020; Hartvigsson et al., 2022).

On the other hand, some studies have looked at EVs as the potential solution for grid failures. Zheng et al. (2019) reviewed vehicle-to-grid (V2G) technology as it can provide an effective and economic solution to integrate the additional charging loads EVs will incur into existing grids. With V2G technology, bidirectional energy exchanges can happen between EVs and grids. Thus, it can store the surplus power during lower-demand periods and feed that back into grids during higher-demand periods to achieve the balance of the supply and demand of electricity. In this situation, EVs are not only the pure electric loads, but also serve as a distributed energy storage system. However, this technology is still in the experimental stage and a number of technical and regulatory issues need to be resolved before it can be widely and effectively used (Zheng et al., 2019).

Tian & Talebizadehsardari (2021) considered shared parking stations (car parks) with V2G capabilities to provide energy resilience for local buildings near to the parking station during times of power outages. Through their simulations, Tian & Talebizadehsardari (2021) found that the EV V2G parking stations could only supply the loads of the buildings for a duration of up to 6hrs depending on the time of day of the outage. This is not a long period of time for a power outage to occur, especially if said power outages are caused by natural disasters which damage infrastructure leading to long repair times, and thus longer power outages. Rahimi & Davoudi (2018) therefore looked at the resilience of residential customers through EVs in the case of unavailability of distribution systems for much more considerably amounts of time, for instance in the aftermath of a hurricane. Rahimi & Davoudi (2018) considered both fully electric and hybrid vehicles in their simulations and as would be expected the hybrid vehicles out-performed the EVs when it came to duration of serving time (the time for which the buildings could rely on the vehicles acting as generators). For example, a Tesla model S could serve between 0.9 and 2.9 days depending on available battery capacity and season of the year, whereas a 2017 Prius offered between 2.0 and 6.5 days.

Kuchta (2022) proposes if a household was to have solar panels on their roof, a common occurrence these days with much literature focusing on scenarios whereby the energy for charging EVs is produced locally (Yang and Wang 2021; Richardson 2013), one may be able to divert this electricity to their vehicles. Yang & Wang (2021) investigated just that, a resilient home energy management strategy to enable residential houses to implement self-power supply during a planned grid outage period. Their proposed strategy incorporated the energy backup capability of plug-in hybrid electric vehicles (PHEV) and residential solar photovoltaic (PV) sources. Through also scheduling home energy consumption pattens, they significantly reduced the impact of a grid outage.

Although with EVs needing to remain stationary in order for V2G to work, this renders EVs useless as a vehicle. In rural areas, their vehicles and the mobility they provide is crucial to life in many cases where alternative transport options are simply unavailable or located too far away. Additionally, commonly seen power cuts these days (due to maintenance) only sees a limited area without power, publicly available charge stations give individuals the option to still be able to recharge away from their home (Griffo 2021). As Kuchta (2022) highlights, “there are more ways to charge an EV in an outage than there are to pump gas”. Its apparent, the debate is still out as to whether power cuts are a cause for concern or not for EV owners.

2.1. Research Contribution

This paper presents the outcomes of simulating multiple scenarios of power outages proposed by the ESEC, with a focus on the impacts of this code on rural individuals with an EV. This paper aims to contribute through:

- Addressing the lack of academic discourse on the EV transition for rural areas
- Investigating the impact power outages could have for EV owners in rural areas

3. Methodology

The small rural village of Bradbourne was chosen as a case study of investigation, located on the outskirts of the Peak District, UK. Bradbourne is home to 84 vehicles spread across 49 households (NOMIS, 2013a; Nomis 2013b), which, for this study have been assumed to all be 40 kWh Nissan Leaf’s with their own 7 kW charge point. Previous work utilised the 2019 National Travel Survey, transformer meter readings from National Grid (the local grid operator for Bradbourne), and various electricity tariff pricing strategies to forecast the charging profiles for 84, 40 kWh Nissan Leaf’s undergoing day-to-day travel patterns over a period of 4 weeks. Further details of this work are outside the scope of this paper but can be found in McKinney et al. (2023). These charging profiles will act as the base for this study, on top of which, power outages, as proposed by the ESEC will be simulated and its impact investigated. Only home charging events are considered in this paper.

3.1. The Electricity Supply Emergency Code

The Electricity Supply Emergency Code (ESEC) (GOV.UK 2019) details plans should a prolonged electricity shortage affect a specific region, or the whole country. This code outlines a method for fair distribution nationally using a process known as “rota disconnections”. The “rota disconnections” propose to split the days up into 3hr segments and during various segments, depending on your postcode location and house, the electricity supply will be cut. To determine which households will be with or without power, they are split into 18 groups (A-U), these will henceforth be referred to as ‘area groups’. As such, the 45 households of Bradbourne which have vehicles, and thus an EV within this simulation, were randomly assigned an area group as shown in Table 1.

Table 1: Area group assignment for each Household of Bradbourne – only households with vehicles (House ID 5-49)

ESEC Block	House ID	ESEC Block	House ID
A	17, 23, 29, 45	L	25
B	14	M	26, 41
C	6, 7, 11, 37	N	15, 31, 43
D	9, 12, 34	P	13
E	10, 28, 33, 38, 47	Q	8, 48
G	32, 46	R	24, 36, 39, 44
H	19	S	27
J	5, 21	T	35
K	16, 18, 22	U	20, 30, 40, 42

Depending on the level of available electricity, multiple disconnection levels were developed as part of the ESEC. These disconnection levels range from loss of electricity for a few 3hr slots per week (Level 1), to complete, continuous, blackout (Level 18). Disconnection Level 10 (GOV.UK 2019) can be seen in figure 1 .

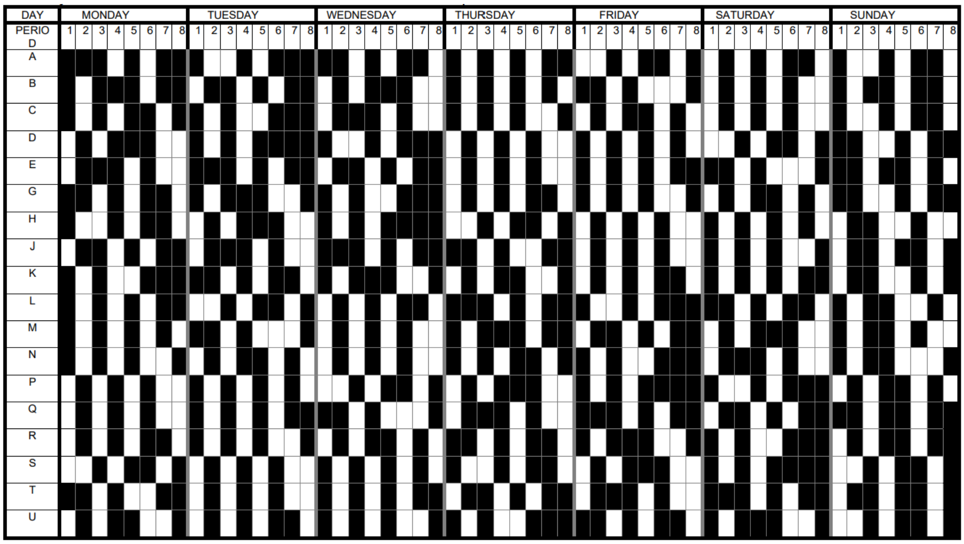

Fig. 1. Disconnection Level 10 from the ESEC

Disconnection levels 1, 5, 10, 12 and 15 proposed by the ESEC have been simulated in this paper, this achieved a wide range of supply interruption and therefore various impact levels on consumers whilst also balancing computational time and effort.

3.2. Charging Regimes

Two charging regimes were chosen to investigate differing behavioural types; firstly as per electricity tariff dictated and secondly, an opportunistic charging regime. Electricity tariff dictated follows protocols as set by the electricity tariff assigned to a household. Households can either be served by a Standard tariff, whereby the price is the same throughout the day and so bares no influence on time of charging, or an Economy tariff, whereby there are cheaper electricity rates between 00:00-07:00, encouraging people to charge within those early hours of the day. As per postcode level electricity meter data (BEIS 2022), for the 49 households of Bradbourne, 37.5% were randomly assigned Standard electricity tariffs and 62.5% were randomly assigned Economy tariffs. The opportunistic charging behaviour on the other hand attempts to accurately reflect real-life human behaviour. Opportunistic charging assumed that, should these planned blackouts go ahead, individuals would cease to follow their electricity tariff pricing structure and opt for a more opportunistic charging approach. The opportunistic approach sees users electing to charge their EV at any time in order to maximise the available state of charge of their vehicle at any one time, therefore ensuring continued use of their vehicles as required. In other words, all households would fall back to standard electricity tariff charging behaviour. To simulate these two charging regimes, it was assumed that all household's EV chargers would have a time delay function (smart functionality), that allows vehicles to be plugged in but wait till the next available charging opportunity arose.

3.3. Algorithm

Custom python scripts were written to simulate these planned power outages proposed by the ESEC. Using the pre-determined EV charging profiles, the algorithm would initially check all pre-existing charging events and cross-reference them with the power outage times per the disconnection level. This would determine if the pre-planned charging events could still go ahead. If a planned charging event was scheduled to occur during a power outage period, the vehicles variables for the duration of that power outage would be recalculated to now account for the lack of charging. Following periods of power outage, when the power returns, should vehicles require charging, and should its location (i.e. at home) allow for a charging event also, then recalculations will also take place to account for this.

4. Results & Discussion

From the 4 week EV Charging profiles (McKinney et al., 2023) two sets of results are shown, displaying two different perspectives: firstly the battery capacity of the EV fleet, and secondly, the energy demand from the 84 charge points of Bradbourne. The following results present just over one week's worth of data for visual ease and allow any simulation start-up transients to settle.

4.1. Battery Capacity

Figure 2 shows the EV 'fleets' total level of charge over time for the original EV Charging profiles and the results for each disconnection period under both charging regimes. From this weekly trend, although there are recharging events occurring in available periods when the power is on during the week, as increased mileage is driven on weekdays as opposed to weekends, this has resulted in a weekly undulating profile. The total battery charge capacity over the course of the week slowly declines, to be replenished to the highest levels at the weekend, for all scenarios.

As expected, disconnection level 15 under the 'Electricity Tariff Dictated' charging regime had the largest impact with a considerable reduction of almost 40% in the total battery charge of the fleet. Compared to the original scenario, all but the highest disconnection level simulation, disconnection level 15, for the opportunistic charging regime method actually improved the overall total state of charge across the fleet. This highlights why such charging behaviour was first developed, in order to simulate how charging behaviours may change during periods of planned power outage. EV owners could act more conservatively and thus charge more in the hours that allow them to do so, and so the battery of every vehicle remains at a higher average SOC. However, these results are deceptive, as they suggest that there is no real concern, even with regards to the higher level disconnection levels. As per fig. 2, this shows roughly a 10% decrease in the total battery charge across all EVs, which is true. However the individual vehicles that constitute this total stored charge are all impacted in different ways depending on their travelling habits and charging capabilities. When considering the individual vehicles which constitute the total state of charge of the fleet, some vehicles fare better than others. Table 2 shows the number of EVs which reach 0% SOC during some point within the 4 week simulation period.

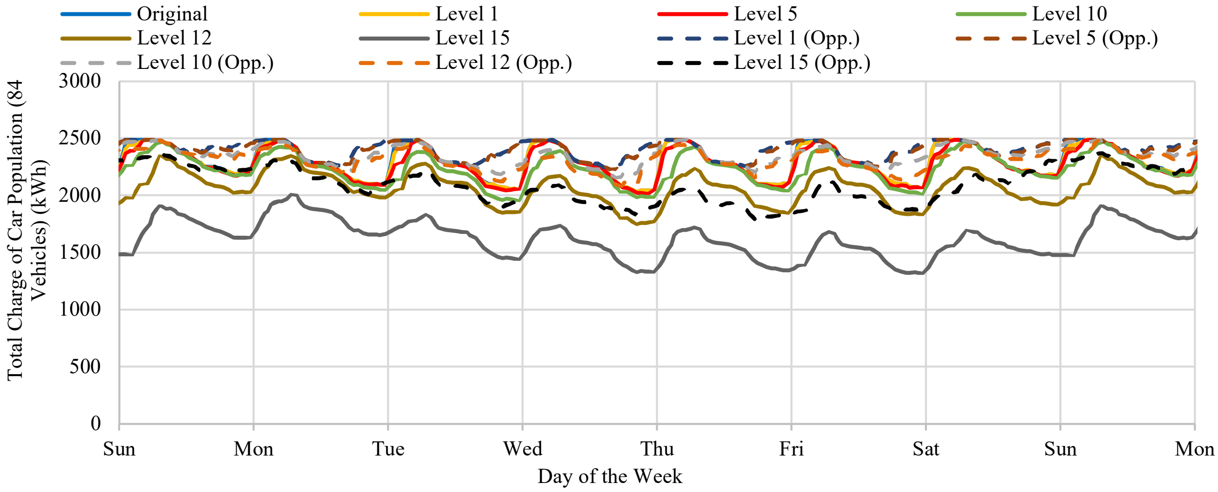

Fig. 2. Total Battery charge of the entire EV population of Bradbourne for both ‘Electricity Tariff Dictated’ and ‘Opportunistic’ charging regimes.

Table 2. The number of EVs that hit 0% SOC at some point during the 4 week simulation of each scenario.

Charging Regime	Disconnection Level	No. of Cars reaching 0% SOC
Electricity Tariff Dictated	Level 1	0
	Level 5	0
	Level 10	1
	Level 12	3
	Level 15	25
Opportunistically	Level 1	0
	Level 5	0
	Level 10	1
	Level 12	1
	Level 15	6

From Table 2, multiple EVs do in fact reach 0% SOC, which is ‘hidden’ when using the total battery charge presentation approach. From a consumer perspective, only when high level disconnection scenarios are simulated does this occur, scenarios which are unlikely to occur in real life should planned power outages ever be invoked per the ESEC. Table 2 also highlights the impact that the opportunistic charging regime has, when compared to the base scenario of the electricity tariff dictated charging regime. When considering disconnection level 15 for both charging regimes, there is a huge reduction from 25 to 6 vehicles that ever reach 0% SOC during the 4 weeks of simulation.

4.2. Charging Energy

Figure 3, in contrast, shows the total charging energy at every half-hour due to all the recharging events occurring during the simulation. These figures show large decreases in the energy demand spikes compared to the original scenario, especially for the opportunistic charging regime based scenarios. The large spikes of the original charging profiles have been reduced, but more charging now occurs during other times of the day, especially for opportunistic regimes. From a generation perspective the total energy charged during the 4 week simulation period for each scenario is detailed in Table 3.

The difference in total energy being delivered to vehicles between each scenario is not significant, with the worst scenario, disconnection level 15, under the electricity tariff imposed charging regime only 2278 kWh below the original level was delivered to the vehicles, representing a loss of only 17.7% in energy to the system over 4 weeks.

Considering the ESEC is a technique for electricity rationing during periods of reduced output, these disconnection levels have not reduced the total energy consumed by very much. Therefore, it could be argued that the purpose of the ESEC has been thwarted, from the EV perspective, by the need to claim energy for travel, albeit at a higher expense than charging off-peak. As expected, the opportunistic charging regime scenarios have maintained the total energy put into the system far better than the electricity tariff imposed regime. This is due purely to the behaviour, and EV owners taking any opportunity they can to recharge their vehicles. Although, by extension this has caused the energy rationing to be ineffective.

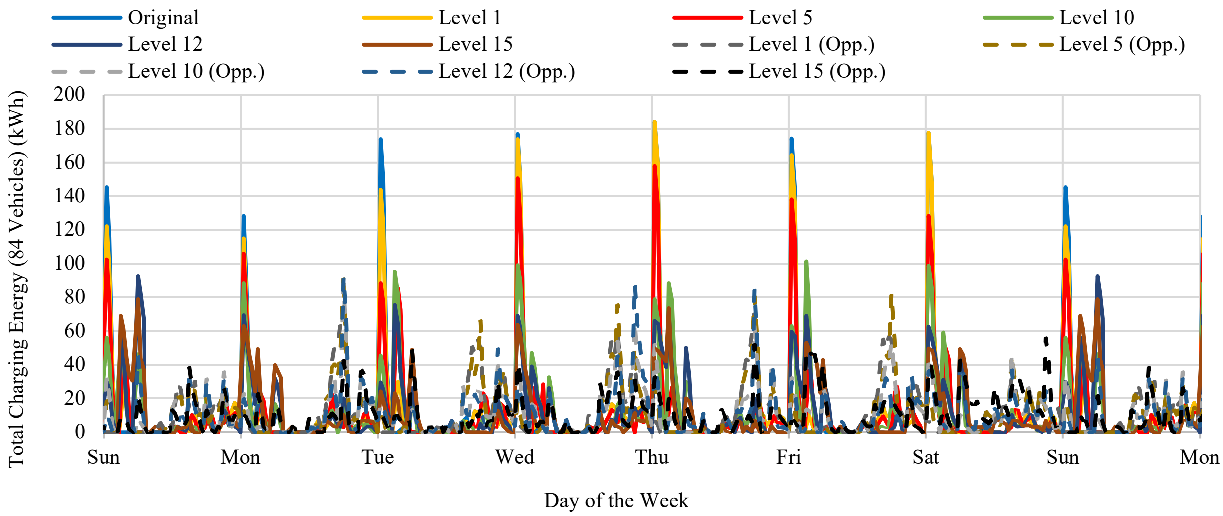

Fig. 3. Charging Energy for both 'Electricity Tariff Dictated' and 'Opportunistic' charging regimes.

Table 3. Total Energy Charge during the total time of simulation for each scenario.

Charging Regime	Disconnection Level	Total Energy Charged (kWh)
Original	-	14,007.87
Electricity Tariff Imposed	Level 1	14,007.87
	Level 5	13,607.24
	Level 10	13,662.64
	Level 12	13,458.49
	Level 15	11,729.52
Opportunistic charging	Level 1	13,994.39
	Level 5	13,998.54
	Level 10	13,917.35
	Level 12	13,857.40
	Level 15	13,513.59

5. Conclusion

This paper presents the results from simulating EV charging requirements under electricity rationing conditions such as if the Electricity Supply Emergency Code (ESEC) was to be invoked. A real life case study was used, based on the rural village of Bradbourne, located in the Peak District, UK. The findings from this study have multiple implications for policy makers, electrical grid planners, energy generation and storage as well as extending the academic discourse for the EV transition in rural areas. Most critical are the findings relating to opportunistic charging, which relates most to how individuals might behave during special circumstances such as those described. Opportunistic charging renders the efforts of the ESEC mute, at least from the perspective of Electric Vehicles. However, it does reduce the large spikes in demand that EV charging places on local grid infrastructure.

Acknowledgements

The University of Sheffield Energy Institute has supported this research.

References

ADE, 2020. Rise in electric car sales could lead to widespread power cuts. ADE.

Ashfaq, M., Butt, O., Selvaraj, J., Rahim, N., (2021). Assessment of electric vehicle charging infrastructure and its impact on the electric grid: A review. International Journal of Green Energy.

Clement-Nyns, K., Haesen, E., Driesen, J., 2010. The Impact of Charging Plug-in Hybrid Electric Vehicles on a Residential Distribution Grid. IEEE Transactions on Power Systems.

Crozier, C., Morstyn, T., McCulloch, M. 2021. "Capturing diversity in electric vehicle charging behaviour for network capacity estimation." Transportation Research Part D, Transport and Environment 93: 102762.

Department for Business, Energy & Industrial Strategy., (2022). Sub-national electricity consumption data. GOV.UK.

Department for Environment Food & Rural Affairs., (2021). Statistical Digest of Rural England.

Department for Transport, (2020). Electric Vehicle Charging Device Statistics July 2020.

Energy Saving Trust, (2021). Ten Point Plan: what progress has been made in the first year?

GOV.UK (2019). Electricity Supply Emergency Code.

Griffo, P., 2021. Yes, you can still drive your ev during a power outage. Energized, Edison International.

Groves, J., Pratt, K., 2023. Our Pick of The Best Electric Car Shares, Forbes Advisor.

Hartvigsson, E., Taljegard, M., Odenberger, M., Chen, P., (2022). A large-scale high-resolution geographic analysis of impacts of electric vehicle charging on low-voltage grids. Energy.

Kutcha, D. M., 2022. Can you charge you electric car during a power outage? Treehugger.com.

Martinenas, S., Knezovic, K., Marinelli, M., 2016. Management of Power Quality Issues in Low Voltage Networks Using Electric Vehicles: Experimental Validation. IEEE Transactions on Power Delivery.

McKinney, T. R., Ballantyne, E. E. F., Stone, D. A., 2023. Rural EV Charging: The effects of charging behaviour and electricity tariffs. Energy Reports.

Nomis., (2013a). Household Size QS406EW [online]. NOMIS Official Labour Market Statistics.

Nomis., (2013b). Car or Van Availability QS416EW [online]. NOMIS Official Labour Market Statistics.

Ofgem, 2020. 9 August 2019 Power Outage Report.

Rahimi, K., Davoudi, M., (2018). Electric vehicles for improving resilience of distribution systems. Sustainable Cities and Society, 246-256.

Richardson, D. B., 2013. Electric vehicles and the electric grid: a review of modeling approaches, impacts, and renewable energy integration. Renewable and Sustainable Energy Reviews.

The Guardian (2022). Government tests energy blackout emergency plans as supply fears grow.

The UK's transition to electric vehicles, Climate Change Committee, 2020.

Tian, M., Talebizadehsardari, P., (2021). Energy cost and efficiency analysis of building resilience against power outage by share parking station for electric vehicles and demand response program. Energy, Elsevier, vol 215.

Wang, Y., Su, H., Wang, W., Z, Y., 2018). The impact of electric vehicle charging on grid reliability. IOP Conference Series: Earth and Environmental Science.

Western Power Distribution., (2022). The Electric Journey.

Williams, F., Philip, L., Farrington, J., Fairhurst, G. 2016. "'Digital by Default' and the 'hard to reach': Exploring solutions to digital exclusion in remote areas." Local Economy 31 (7): 757-777.

Yang, Y., Wang, S., (2021). Resilient residential energy management with vehicle-to-home and photovoltaic uncertainty

Zheng, Y., Niu, S., Shang, Y., Shao, Z., Jian, L., (2019). Integrating plug-in electric vehicles into power grids: A comprehensive review on power interaction mode, scheduling methodology and mathematical foundation. Renewable and Sustainable Energy Reviews.