Assessing the Robustness of the Urban Transport–Energy Nexus: Evidence from the Glasgow City Region

Si Chen[1], Benoit Couraud[1], Wei Bi[2], Jamie Blanche[1], Merlinda Andoni[1], Kristen MacAskill[2], David Flynn[1]
1 University of Glasgow, United Kingdom, Si.Chen@glasgow.ac.uk, benoit.couraud@glasgow.ac.uk, jamie.blanche@glasgow.ac.uk, merlinda.andoni@glasgow.ac.uk, david.flynn@glasgow.ac.uk

2 University of Cambridge, United Kingdom, wb316@cam.ac.uk, kam71@cam.ac.uk

Abstract

Rapid electrification of transport and the integration of renewable resources pose new stresses on urban electricity distribution networks. Understanding these risks is vital for developing advanced methodologies that support adoption of electric vehicles (EVs), adaptation to climate risks, and resilience of the transport–energy nexus. Existing research has explored renewable integration and smart grid solutions, but less attention has been given to how distribution network faults interact with emerging EV charging demand in dense urban settings. This paper addresses this gap through a case study of Glasgow City. Using power flow analysis, the study shows that climate events resulting in faults on the grid could considerably impact the grid supply points, whereas the voltage levels in a urban environment will stay within boundaries.

Keywords: urban resilience; transport-energy nexus; urban energy system

Introduction

Urban electricity networks are facing several challenges that include the electrification of heat and transport, but also widespread distributed generation and an increase of climate-related disturbances (Wang, Yang, Fang, Wang, & Wu, 2023). This results in highly complex systems, where weather dependent variables influence the whole energy system (Shi, Liu, Zeng, Hui, & Li, 2022), and can impact its stability (Shi, et al., 2021) (Barnes, Nagarajan, Yamangil, Bent, & Backhaus, 2019).

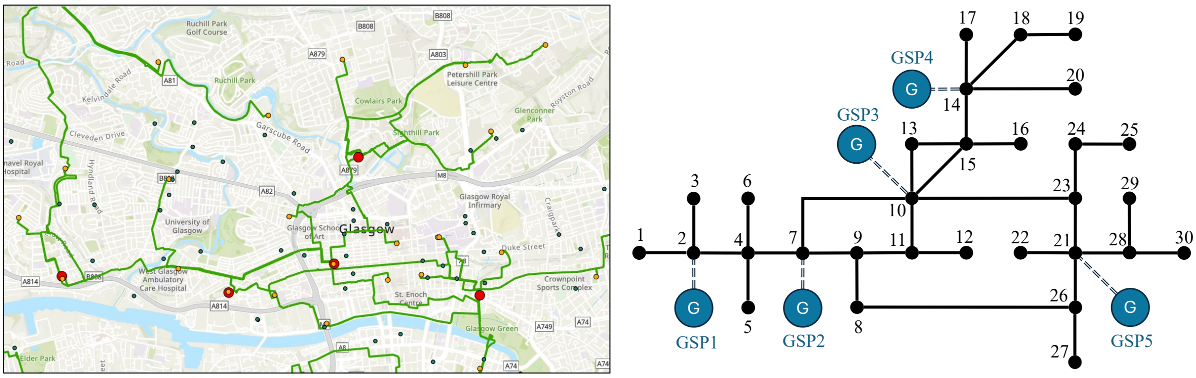
In this study, we explore the resilience challenges of urban electricity networks with high penetration of EVs, through an analysis of Glasgow's 33 kV distribution network. Using a digital model of this network, we assess how Grid Supply Point (GSP) failures can impact the normal operation of the network even in scenarios with high penetration of EVs, underscoring the importance of intelligent coordination strategies across transport–energy (T–E) networks to strengthen resilience.

Methodology

The study simulates the behaviour of an urban electrical grid in the case of future scenarios involving high EV penetration and climate events. Three aspects were considered.

A. Modelling the 33 kV Distribution Network

The 33 kV electric distribution network of Glasgow was modelled as a multi-node feeder network of 30 nodes as shown in Figure 1.



(a) (b)

Figure 1. Distribution network (33 kV) of Glasgow urban area. (a) Network map with public EV charger locations in ArcGIS, (b) Simplified 30-node feeder diagram.

Network data were obtained from the local distribution network operator (SP Energy Networks, 2025). Figure 1 shows the modelled network, represented by 5 Grid Supply Points (GSPs) that are well interconnected to enhance resilience during faults.

B. EV Charging Demand under Transport Electrification

In addition to the real network model, we incorporated historical load data from primary substations and integrated real public EV charger locations and consumption data (Charge Place Scotland, 2025). To assess the impact of transport electrification, we generated synthetic charging load profiles for higher penetration scenarios ranging from 1.4%, current EV penetration rate (Consumer Scotland, August 2024), to 84%. The total load at each substation thus comprises both residential/commercial demand and EV charging demand.

C. Integration of Climate Events

Finally, we assessed network resilience to climate-related events by simulating fault scenarios on GSPs to evaluate the system's response when the total load remains unchanged. Historical fault records indicate that over 90% of incidents are attributed to cable failures, with falling trees during high windstorms and flooding being particularly significant contributors (SP Energy Networks, 2024).

By running power flow simulations with these three aspects, we can assess the network status in future scenarios with high EV penetration and faults from GSPs due to climate events.

Results

Simulations have shown that climate events that would lead to GSPs faults have two main impacts on the network: firstly, they affect adjacent GSPs by requesting more power from them, and secondly, they modify the network voltage profiles.

A. Impact on Electricity Supply Points

Due to the meshed nature of the distribution network, GSPs can support each other during a fault. When one GSP is disconnected, adjacent GSPs supply its load, which may increase the risk of overload.

Figure 2 illustrates the GSP load redistribution under different fault cases and EV penetration. For stress testing, peak charging demand was used to capture the most critical conditions. For example, disconnecting GSP1 shifts most of its load to GSP2 with limited impact elsewhere.

In contrast, disconnecting GSP3 leads to load redistribution across GSPs 2, 4, and 5, reflecting its central position in the network.

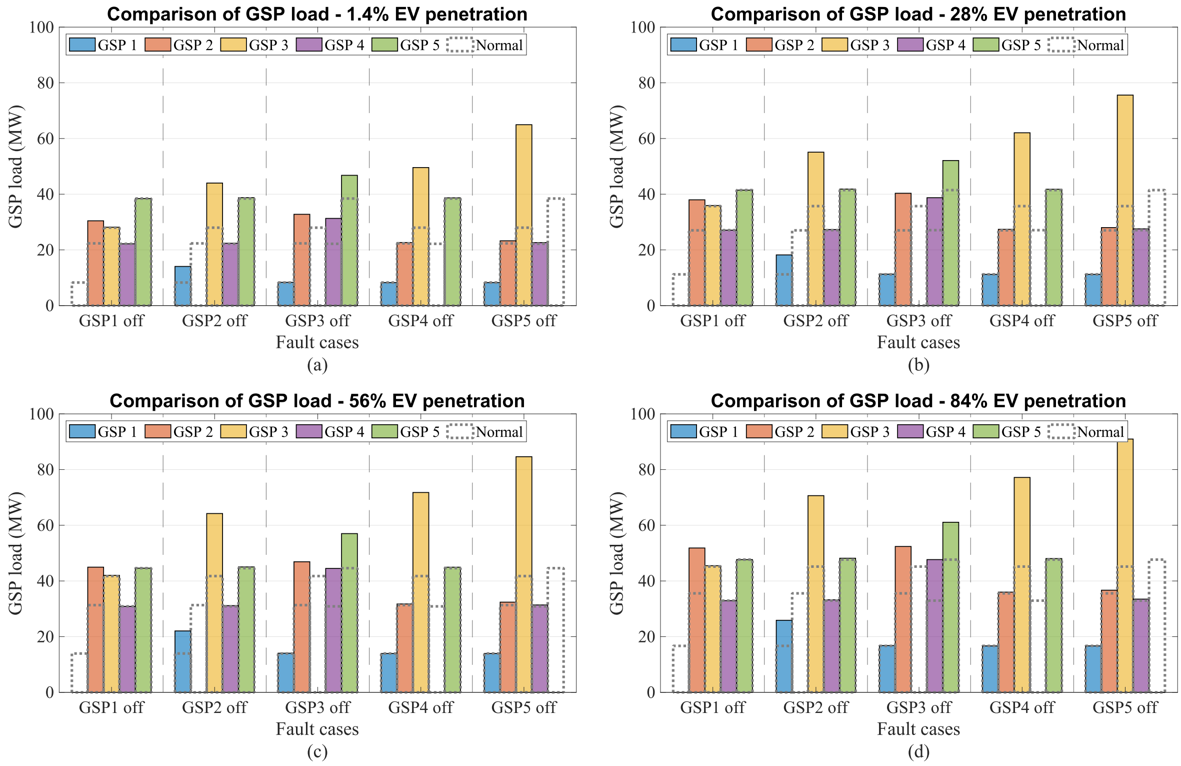


Figure 2.GSP load changes under different fault cases and EV Penetration Projections.

These results highlight that certain GSPs are more susceptible to overloading when adjacent GSPs are offline. This vulnerability increases with the growth in EV charging demand due to transportation electrification, as shown in Figure 2 (d), underscoring the need for future mitigation and shared resilience strategies at the T-E nexus.

B. Impact on Network Voltage

Voltage levels across nodes must be maintained at 94% of their nominal value as per contractual agreement. As shown in Figure 3, our simulations show that when a local GSP is offline, the new supply profiles lead to voltage drops up to 0.4% compared to normal conditions, which does not impact considerably the operation of the network. This is due to the fact that networks in urban environments are very dense, with small cable lengths, yielding to very small voltage drops.

In summary, these findings show that the network voltage plan is resilient to single climate faults but the resilience of supply points to climate events should be strengthened.

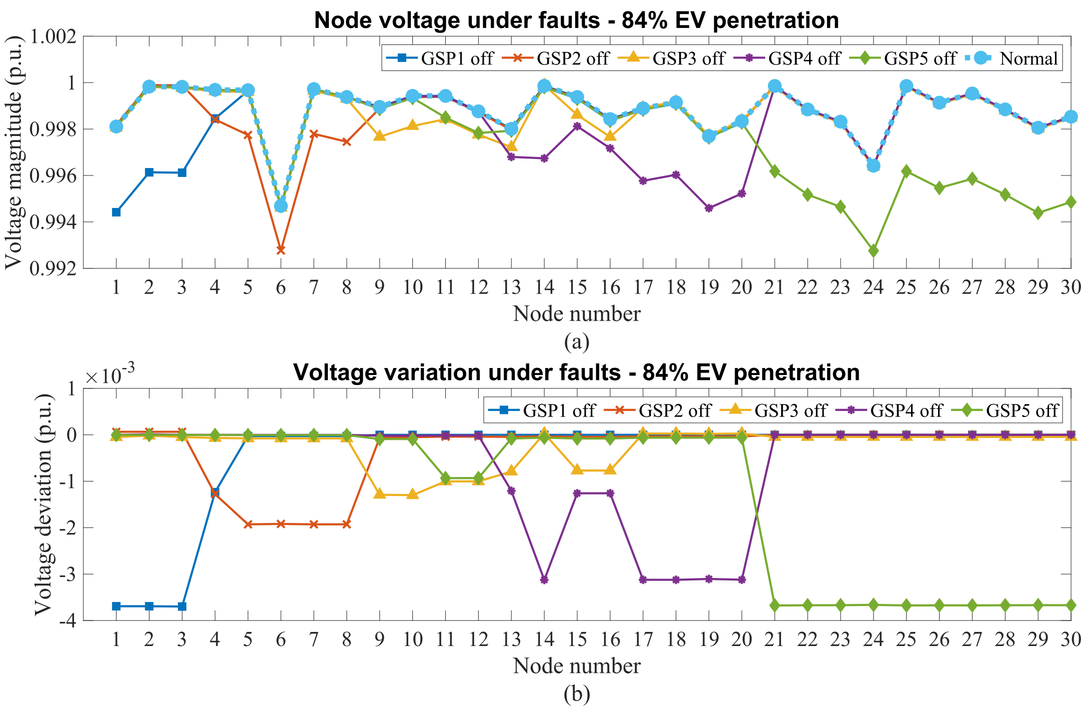


Figure 3. Node voltage and their variations under fault cases.

Conclusion

This study presents a system-level analysis of an urban 33 kV distribution network with high penetration of EV chargers. By considering GSP faults scenarios due to cable failure during climate-related events, our simulations highlight that adjacent GSP become more exposed to overloading, particularly with high EV charging demand.

Future research will examine scenarios with multiple weather-induced faults and propose mitigation strategies that leverage transport-sector flexibility to support the electrical network, highlighting the resilience benefits of transport–energy system coupling.

Acknowledgements

This work was supported by EPSRC and UK Department for Transport for Decarbonised Adaptable and Resilient Transport Infrastructures (DARe) project (EP/Y024257/1).

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