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Plugging-In Caledonia: Location and Utilisation of Public Electric Vehicle Chargers in Scotland

Kathleen Davies *, Edward Hart and Stuart Galloway

Department of Electrical and Electronic Engineering, University of Strathclyde, 16 Richmond Street, Glasgow G1 1XQ, UK; edward.hart@strath.ac.uk (E.H.); stuart.galloway@strath.ac.uk (S.G.)
* Correspondence: kathleen.davies.2017@uni.strath.ac.uk

Abstract: Electrification of private cars is a key mechanism for reducing transport emissions and achieving net zero. Simultaneously, the development of public electric vehicle (EV) charging networks is essential for an equitable transition to EVs. This paper develops and analyses an extensive, nationally representative dataset of EV-charging sessions taking place on a key public charging network in Scotland between 2022 and 2024 to gain insights that can support the development of public charging infrastructure. Data were collated from 2786 chargers and analysed to establish a detailed characterisation of the network's organisation and utilisation. The network considered is government-owned and was fundamental to the Scottish rollout of public chargers. Key insights from our analysis of the developed dataset include quantified disparities between urban and rural charger use-time behaviours, with the most rural areas tending to have charging activity more concentrated towards the middle of the day; an analysis of the numbers of deployed chargers in areas of greater/lesser deprivation; utilisation disparities between charger technologies, with 35% of slower chargers being used at least once daily compared to 86% of rapid/ultra-rapid chargers; and demonstration that charging tariff introductions resulted in a 51.3% average decrease in sessions. The implications of our findings for policy and practice are also discussed.

Keywords: electric vehicles; public EV charging; EV-charging infrastructure; EV-charging sessions; EV-charger utilisation; EV-charging behaviour

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1. Introduction

Domestic transport is the largest emitting sector in Scotland [1] and therefore represents one of the greatest risks with respect to achieving net zero. The transition away from petrol and diesel cars towards electric vehicles (EVs) has been identified as having the potential to drive a significant reduction in transport emissions in the Scottish context [2]. Therefore, the electrification of private cars will play a critical role in reducing transport emissions and achieving key governmental targets, including the Scottish Government's legally binding objective to reach net zero by 2045 [3]. However, the realisation of a transition to EVs requires that EV-charging infrastructure be available and accessible.

Home charging will play a significant role. Zap-Map, a major EV charging infrastructure-mapping service in the UK, conducted a survey in 2022 of over 4300 of their users. A key finding of this survey was that 84% of surveyed EV owners from across the UK possessed a residential charger [4]. However, the public EV-charging network will have an undeniably important role. For instance, 90% of survey respondents reported regular use of public chargers [4]. Furthermore, the public network will be crucial for those requiring access to a charger to complete a journey or for those without access to residential or workplace charging facilities [5]. Additionally, range anxiety and perceptions of the available range of EVs can impact charging behaviours [6,7] and sometimes result in increased charging during journeys. Therefore, the public charging network will play a key role in enabling the equitable transition to EVs, ensuring EV use is not reserved only for those with adequate finances and parking conditions to host a home charger, or for those who only tend to complete shorter journeys.

Moreover, there is evidence from other geographical contexts, namely the USA, and specifically New York City, that public EV-charging infrastructure tends to be disproportionately distributed in higher-income, more advantaged areas [5,8] (although different geographical contexts may feature different socioeconomic structures and societal challenges, complex geographies and terrains, levels of development and funding for transport networks, and attitudes towards car usage and EVs). Additionally, the positioning of charging infrastructure can influence local EV adoption, meaning that a chicken-versus-egg feedback effect can exist between installation of chargers and EV adoption [9–11], and there is evidence that charger installation and availability supports EV adoption [12,13]. These factors highlight the importance of careful planning of chargers so that no groups are left behind or unable to access sufficient public charging infrastructure.

To support the transition to EVs in Scotland, the Scottish Government has pledged to install 24,000 new public EV chargers by 2030 [3]. The location of these chargers, along with further considerations, such as charging tariffs and the power rating of charging infrastructure, will be important. Given the importance of ensuring this infrastructure is planned equitably while effectively meeting the needs of both current and future users, it is essential to understand how the existing public network is currently distributed and utilised. These insights can inform strategies to support EV adoption and have broader implications for energy systems policy and management.

This paper, therefore, analyses available public charging data from a major public network in Scotland to inform the future development of Scotland's EV public charging network. More specifically, an extensive Scottish EV-charger dataset is compiled and analysed in order to explore the following research questions:

1. Where are Scotland's public EV chargers currently located?
2. When are Scotland's public EV chargers typically used?
3. What impact does the introduction of tariffs have on Scottish public EV charger usage?
4. What characteristics do the most utilised public EV chargers in Scotland have?

In addressing these research questions, this paper will consolidate the broader understanding of public charging utilisation in the international context and contribute to a deeper understanding of the utilisation of public EV chargers (particularly disparities in user behaviour across different areas), the impact of the introduction of tariff programmes, and the key areas where government intervention and policy could support the development of the charging network in Scotland. Additionally, in considering data pertaining to a public charging network that featured a publicly funded rollout strategy, key insights into public EV charging featuring this relatively uncommon approach are provided. The importance of the electrification of private cars to achieving critical emissions reductions, alongside other Scottish Government commitments surrounding the installation of further public charging infrastructure, makes it pertinent to gain insights into public charging in Scotland. By offering concrete numbers quantifying impacts and evidence-based recommendations, the insights discussed in this paper can guide policymakers, charge point operators, and power system operators to further develop an equitable public EV-charging network that will continue to enable the transition towards EVs and reduced transport emissions.

The remainder of this paper is structured as follows: Section 2 provides a background to the research topic and discusses the relevant previous literature; Section 3 outlines the methodology and details the developed dataset; Section 4 details and discusses the results of the analysis; Section 5 provides a discussion of the implications the results have for policy, transport planning, and future work; and Section 6 concludes the paper.

2. Background

2.1. Public Charging Utilisation and Behaviour

To explore utilisation trends of EV public-charging infrastructure, prior research has undertaken analyses of EV charging-session data. Some of these studies consider public charging in similar geographic contexts to this work (i.e., Scotland [14–16] or the UK [17]), while others focus on different geographical contexts, including the USA [18–20], Germany [11,21], the

Netherlands [22,23], and Ireland [24]. Additionally, some other studies use public EV-charging data from Scotland and apply them to technical models to give insight into charging network utilisation [25–27] and network development [28], and a study of charging behaviour in Norway uses data from a stated preference survey [7].

Regarding research focused on public EV charging in Scotland, Makwana [15] analyses charging-session data from the ChargePlace Scotland public EV-charging network, comparing data for the months of August in 2013 and 2014 to examine growth and utilisation of the network. The findings showed an increase of 366% in the number of charging sessions that occurred between August 2013 and August 2014, and that 55% of chargers were used at least once in August 2014. A further study conducted by Makwana [16] considered the month of August also in 2015 and 2016. Similarly, there was an increase of 348% in the number of sessions between August 2014 and August 2015, and an increase of 102% in the number of sessions between August 2015 and August 2016. Additionally, 68% of chargers were used at least once in August 2015, and 75% used at least once in August 2016. No data were available for the number of chargers on the network in August 2013; however, the ratio of ChargePlace Scotland chargers to EVs in 2014, 2015, and 2016 was relatively stable at circa one charger for every two EVs. It is important to note that the data used in these analyses are from a time period when EV adoption was in its infancy (i.e., there were 1071 licensed EVs [15] in Scotland by the end of 2014, compared to 38,512 by the end of 2022 [29]), and there were very few chargers on the network, so few data were available (i.e., August 2013 had 619 recorded sessions and August 2014 had 2885 recorded sessions [15], while August 2015 had 12,939 recorded sessions and August 2016 had 26,119 [16]).

Looking to 2022, the ratio of ChargePlace Scotland chargers to licensed EVs in Scotland has regressed to approximately 1 charger to 16 EVs [29,30] (although public chargers on other networks are now more prevalent). In 2014, the European Union Alternative Fuel Infrastructure Directive set out a target for member states to achieve a ratio of 1 public charger per 10 EVs; however, this target was updated to a goal of providing 1 kW of power via public chargers per EV as the ratio of chargers to EVs differs between countries [31]. For example, the Netherlands has a particularly high ratio of public chargers to EVs, with 1 charger per 5 EVs. Meanwhile, Spain and Sweden have a ratio of 1 charger per 15 and 17 EVs, respectively. Additionally, Norway has a relatively low ratio of chargers to EVs, with 1 charger per 34 EVs [32]. Although it is likely that there are interactions between the ratio of public chargers to EVs and EV adoption, the relationship between these two entities is not obvious. Specifically, despite Spain and Sweden having similar ratios, the number of EVs per 100,000 people varies, with Spain having 372 EVs per 100,000 people and Sweden having over eight times as many, with 3105 EVs per 100,000 people. The Netherlands, with its low ratio of chargers to EVs, has 2637 EVs per 100,000 people (relatively similar to Sweden); meanwhile, Norway, with its high ratio, has a significantly higher EV penetration, with 13,381 EVs per 100,000 people [33]. Additionally, the ratio of chargers to EVs may disguise strategic decisions to invest more significantly in faster chargers [32,34]. For example, although the Netherlands has a more favourable public-charger-to-EV ratio, the average power of chargers in the Netherlands is 19 kW compared to 81 kW in Norway [33].

Hunter et al. [14] introduced a method informing the siting of EV chargers in rural Scotland. The processes involve identifying areas far from existing chargers and identifying demand for chargers by conducting a 'queuing analysis' where the time between sessions is considered to identify the likelihood of chargers experiencing demand at difficult-to-cope-with levels. Not only was the queuing analysis able to identify how in-demand chargers were; it was also designed to highlight chargers possibly experiencing technical issues and chargers that may experience problematic demand in the future. Interestingly, this study found that the likelihood that a charger would experience queuing was linked to ferry schedules. This analysis focuses on rural areas only, in particular, mainly just three Scottish local authorities, and provides a specific site-selection method for remote areas rather than a comprehensive view of public charging across Scotland.

Expanding focus slightly to include other nations of the UK, Bayram et al. [17] consider data from EV chargers included on a UK-wide public network. It was found that on weekdays, peaks in session start time occurred at 8 a.m. and 5:15 p.m., while on weekends, the peak-session start time was 10 a.m. A case study was also conducted to explore the impact of 'time-of-use' tariffs, where charging fees are reflective of energy cost and demand to encourage users to charge at off-peak times instead of times of high demand. It was found that these have potential to facilitate a shift in peak utilisation to times of lower energy demand. However, the chargers located in Scotland in this analysis appear to be mostly concentrated in the two major cities, Glasgow and Edinburgh, meaning this analysis is less able to provide a holistic understanding of charging in Scotland. Additionally, the chargers considered do not exceed a power rating of 22 kW; EV adoption was still in early stages at the time of writing; and the dataset explored is relatively small, containing only three months of data.

As mentioned, other works also use Scottish public EV-charging data to propose methodologies for facilitating network expansion and estimate charger utilisation through application to technical models. For example, Akil et al. [25] apply a Monte Carlo simulation to a small dataset of public EV-charging sessions in Perth and Kinross covering a single daytime period. In doing so, charging profiles are modelled, and it was predicted that, in the case where charging is not controlled via time-of-use tariffs or similar schemes, weekdays would see peak charging-session start times of 1 p.m., 4 p.m., and 6 p.m., while weekends would see peak session start times at 12 noon and 2 p.m. Golsefidi et al. [28] propose a methodology for efficiently expanding the public EV-charging network, applying their method to a case study of Dundee City and using data on the energy transferred by chargers across that area. Their case study allows for an evaluation of infrastructure development strategies to be made. Orzechowski et al. [27] propose a methodology for projecting public EV-charging demand in the medium-term future and validate their method using charging session data from eleven public chargers in Scotland. Meanwhile, Ma and Faye [26] propose a model for forecasting the occupancy of public EV chargers to facilitate greater user convenience. To compare their proposed model to existing techniques, public EV-charging data from Dundee were used.

Concerning work from different geographical focuses, Borlaug et al. [19] consider public EV charging-session data from the USA exploring chargers of lower (i.e., between 3 kW and 19.2 kW) and higher (i.e., between 50 kW and 350 kW) power ratings at different location types (e.g., offices, shops, and leisure centres). Key findings of this work include that 50% of chargers considered in the analysis were responsible for meeting 90% of charging demand, that utilisation of lower-power chargers tends to reduce as the quantity of local lower-power chargers increases (while this effect was not observed to the same extent for higher-power chargers), and that free charging is associated with greater utilisation. It was also found that lower-power chargers were more likely to experience higher levels of overstay behaviour (when a vehicle remains plugged in but is no longer charging) than higher-power chargers. Specifically, it was found that charging sessions taking place on lower-power chargers experienced between 30% and 76% of session duration (depending on charger location type) not actively charging, compared to between 5% and 11% of charger duration for higher-power chargers. It was proposed that the location type that lower-power chargers tend to be found in may contribute to this effect, as the types of activities associated with the location types may be the main factor driving parking duration rather than required charging time.

Additionally, Morrissey et al. [24] explore public EV-charging data from Ireland, aiming to understand the uncertainties surrounding user behaviour, particularly in terms of charging-session start times and energy consumption, to inform infrastructure development. Again, chargers in this study are categorised by their location type (e.g., car parks, petrol stations, and on-street areas) and power rating. It was found that higher-power chargers saw a relatively high amount of variation in average daily sessions between chargers and found that utilisation of chargers was similar across the different location types considered;

however, petrol stations tended to have shorter charging sessions compared to the other locations. This work also discusses the economic viability of public chargers, pointing to reports that higher-power chargers may require up to six daily charging sessions to be commercially feasible, while lower-power chargers may require at least two daily charging sessions.

In general, the literature from other geographical contexts finds that utilisation of the public network is relatively low [11,19,21,24], that faster chargers tend to be preferred and experience higher utilisation [7,17,19,24], and that different types of areas will generally have unique charging infrastructure requirements [23,24]. Furthermore, the presence of facilities (e.g., cafes and shops) near chargers has been identified as an important factor contributing to users' decisions to charge [7]. Additionally, some studies [11,18,22,23] focus on charge session duration to inform public charging utilisation. Although this can be an important factor in understanding charging behaviours and quantifying charging infrastructure needs, it can be misleading due to potential overstay behaviour, which can be particularly impactful when it is not discouraged (e.g., situations where users pay per kWh rather than per time unit [22] with little or no penalty for staying over a specified time duration).

The studies from different geographical contexts provide valuable insights into public EV-charging utilisation, and much can be learned and applied from their findings. However, there may be limitations on their relevance to the Scottish public charging landscape for a plethora of reasons (e.g., different complex geographies, socioeconomic factors, and types of urban and rural communities) but particularly due to the somewhat unconventional rollout strategy of public charging in Scotland, further described in Section 2.2. Additionally, some works focus on time periods early on in the context of EV adoption [24] and analyse relatively small datasets [18,24]. Therefore, ongoing research efforts considering public EV charging-session data will help consolidate a broader understanding of public EV charger utilisation to inform charging-network development.

2.2. Public EV Charging in Scotland and Socioeconomic Context

The data used in the work of this paper are EV-charging sessions that took place on the ChargePlace Scotland network [35]. ChargePlace Scotland is a key public charging network in Scotland, with just under 3000 of Scotland's 5500 public chargers being hosted on this network today [36]. The network is owned and was instigated by the Scottish Government [35], and the distribution of chargers across Scotland hosted on the network as of March 2024 is shown in Figure 1.

The initial rollout strategy of public charging infrastructure in Scotland through the ChargePlace Scotland network is relatively uncommon. While many other countries opted for private sector-driven rollout [14], in Scotland, government funding was awarded to public and private bodies to facilitate their ownership and operation of public EV chargers [37], with local authorities making up a significant proportion of charger owners [14]. Therefore, ChargePlace Scotland itself does not own or operate the chargers, but it does hold other responsibilities, such as customer service, implementing simple remote fixes for some faults, and data reporting. A key advantage of this rollout approach is the far-reaching nature of this single network, meaning that there is ease of use for EV drivers, as only one network membership and access card is needed to charge across the country. Additionally, this means that data from the ChargePlace Scotland network can give insights into EV charging for the whole of Scotland, rather than for only selected regions or area types [14].

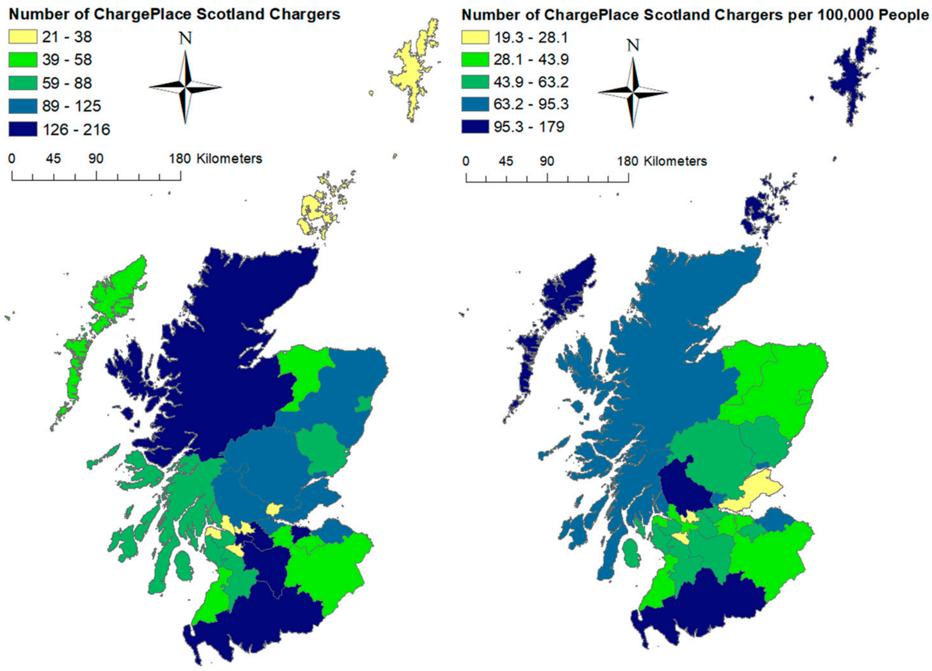

Figure 1. The number of chargers (left); and number of chargers per 100,000 people (right), on the ChargePlace Scotland public EV-charging network as of March 2024, including data on population and the number of ChargePlace Scotland chargers (reprinted from Refs. [35,38]) and thematic layer representing local authority boundaries (reprinted from Ref. [39]).

2.2.1. ChargePlace Scotland Charging Tariffs

Government funding for installing chargers was awarded to charger operators on the condition that the chargers would be free to use for at least one year to promote EV uptake. Beyond this point, the individual charger owner is free to set their own tariffs and terms of use for the chargers they own and operate [37], and different charger owners have therefore introduced tariffs to varying degrees at different times. Specifically, this means that there are disparities between tariff programmes and when they have been introduced for chargers across the country. Moreover, some chargers remain free to use on the ChargePlace Scotland network (e.g., the chargers at Braehead Shopping Centre remained free to use at time of writing [35]). The introduction of tariffs is thought to be important in encouraging private investment in Scotland's public charging landscape, and enticing this private investment has been challenging as a result of the inclusion of free charging in the market. Private investment is thought to be crucial to the effective development of the public EV-charging network, as it is infeasible for public funds alone to bear the financial burden of network expansion [37].

For local authority-owned chargers, the local council sets the charging tariff and any other terms of use, such as overstay fees or limits on times of use/charge duration. During the time period concerning the dataset used in this work, twelve local councils introduced charging tariffs for their chargers. Notably, three local authorities still offered free charging throughout the dataset time period, namely North Ayrshire, East Ayrshire, and South Ayrshire [40,41]. Additionally, East Lothian Council introduced a time-of-use tariff for a small number of chargers on the ChargePlace Scotland network. This time-of-use tariff specifies that, for the chargers included in the trial, charging between the hours of 4 p.m. and 8 p.m. will incur an increased fee by ten pence per kilowatt hour to attempt to shift charging demand away from times of peak energy demand [42]. For context, Figure 2 provides an overview of the local authorities in Scotland.

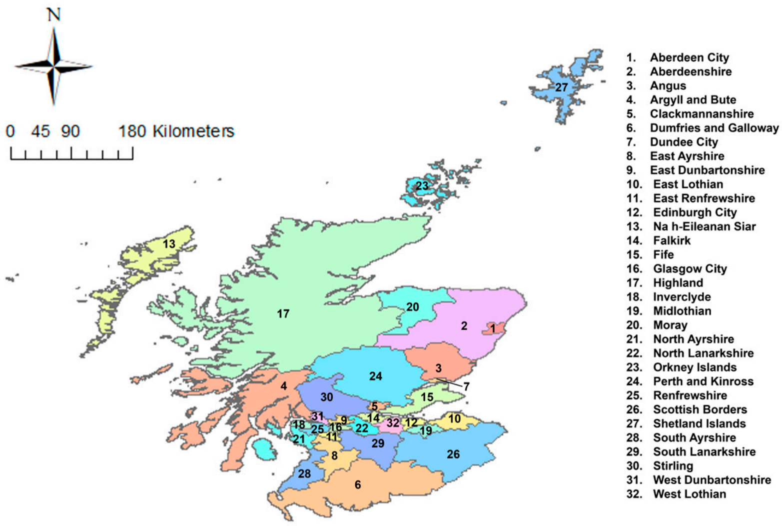

Figure 2. Map of Scotland's local authority areas (reprinted from Ref. [43]), including thematic layer representing local authority boundaries (reprinted from Ref. [39]).

2.2.2. Charger Technology

As mentioned in Section 1, charger-power rating is an important consideration when exploring charging infrastructure. A higher charger-power rating commonly indicates a faster speed of charge, and the power rating of chargers on the ChargePlace Scotland network is generally categorised into three charger speeds: AC (up to 22 kW), rapid (50 kW), or ultra-rapid (150 kW). AC chargers can take between three and ten hours to completely charge an EV, while rapid and ultra-rapid chargers can completely charge an EV in as little as half an hour [44].

Charger-power rating not only has implications for the speed of charge but can also have implications for the cost of the infrastructure. There can be disparities in the cost of charging equipment for chargers of different speeds, and, specifically, it has been reported that AC chargers can cost up to GBP 5000 for one charging unit, while rapid/ultra-rapid chargers can cost up to GBP 26,000 for one charging unit [45]. This shows that rapid and ultra-rapid infrastructure can be more than five times more expensive than an AC charger. Note that other costs will be associated with charger installation, over and above the cost of the actual charger unit (e.g., for grid connection, signage, turfing, cabling, and placement of safety barriers), and these vary depending on the number and speed of chargers being installed. For example, it is estimated that connection costs for one rapid charger could be up to GBP 3000, and this cost would be roughly equivalent to the connection cost for up to three AC chargers [46]. Therefore, charger speed and the associated financial implications are important factors when planning charging infrastructure.

2.2.3. Socioeconomic Indicators in Scotland

For spatial distribution of public chargers in Scotland to be equitable, it is important that the needs of all diverse groups are met. Particularly, both urban and rural, accessible and less accessible, and deprived and less deprived communities should have sufficient public EV-charging infrastructure. Valuable sources of information about deprivation and accessibility, with the latter providing a standardised categorisation of how urban or rural an area is in Scotland, are the Scottish Index of Multiple Deprivation [47] and the Urban–Rural Classification [48].

The Scottish Index of Multiple Deprivation is a holistic indicator accounting for deprivation across various categories, namely income, employment, education, health, geographical accessibility, crime, and housing [47]. The index gives each area a value between 1 and 6976, with 1 being the most deprived and 6967 being the least deprived. Each segment of the Scottish Index of Multiple Deprivation is weighted differently so that some categories contribute more to the final index than others. Specifically, income and employment categories each make up 28% of the overall score; health and education each contribute 14%; and the remaining categories of geographical accessibility, crime, and housing contribute 9%, 5%, and 2%, respectively [49].

Although the Scottish Index of Multiple Deprivation can give an overall understanding of deprivation in an area, it is also possible to isolate each element of the index and consider its score individually. The Geographical Accessibility Index element of the Scottish Index of Multiple Deprivation will be particularly relevant to transport planning. This indicator itself can give a holistic indication of how accessible an area is, accounting for access to public and private transportation, access to key services (e.g., GPs, schools, post offices, and shops), and access to digital services (i.e., broadband connection) [49]. Both the Scottish Index of Multiple Deprivation and the Geographical Accessibility Index can be split into quintiles, where the first quintile represents the 20% most deprived/least accessible areas, the second quintile represents the 40% most deprived/least accessible areas, and so on. On the other end of the scale, the fifth quintile represents the 20% least deprived/most accessible regions.

There are multiple forms of the Urban–Rural Classification; however the eight-fold indicator is used in this work, as it gives the most detailed representation, particularly of the most remote areas [50]. The eight-fold Urban–Rural Classification assigns a value between 1 and 8 to each area, where 1 is the most urban category and 8 is the most rural. Specifically, the classifications are: 1—'large urban areas'; 2—'other urban areas'; 3—'accessible small towns'; 4—'remote small towns'; 5—'very remote small towns'; 6—'accessible rural areas'; 7—'remote rural areas'; and 8—'very remote rural areas'. For classifications 1 and 2, 'large urban areas' have populations of over 125,000 people, while 'other urban areas' have populations between 10,000 and 124,999 people. For classifications that feature the terms 'small towns' and 'rural areas', these have populations ranging from 3000 to 9999 people and less than 3000 people, respectively. Classifications that are categorised as 'accessible' are within a half-hour drive of a community of at least 10,000 people, while classifications categorised as 'remote' are between a half-hour and hour drive of a community of at least 10,000 people, and 'very remote' classifications are over an hour's drive from such a community [48]. The Urban–Rural Classification, in combination with the Scottish Index of Multiple Deprivation and its Geographical Accessibility Index element, can give valuable context to the socioeconomic landscape of individual areas in Scotland.

Different transportation trends can be seen across the different Urban–Rural Classifications and Scottish Index of Multiple Deprivation quintiles. The Scottish Household Survey [51] is conducted annually via in-person interviews to provide official statistics on a plethora of issues and is used by the Scottish Government to inform policy. Regarding transportation, respondents are asked about their travel habits and, in some cases, asked about their previous days' travel specifically. Transportation trends in Scotland are reported nationally, and some data are also available on the basis of the Urban–Rural Classifications and Scottish Index of Multiple Deprivation quintiles. For example, according to the 2022 Scottish Household Survey [51], 55.2% of journeys made in Scotland were completed by driving a car. It was also reported that, overall, across Scotland, most journeys (specifically 15.9% of journeys) occur on a Friday. The lowest proportion of journeys occur on a Monday (specifically 12.8% of journeys), which is closely followed by Sunday, when 13.1% of journeys tend to be made.

Considering differences between urban and rural travel, it was reported that rural dwellers tended to make more journeys by car and fewer by active travel and public transport compared to their urban counterparts. Specifically, 44% of journeys were completed by driving a car in the most urban areas, compared to 69% of journeys in the most rural areas. Additionally, rural people tended to travel greater distances and were more likely to own a private car, and rural commuters who drive were less likely to have access to public transport alternatives to complete these trips compared to urban residents. Furthermore, considering differences between the most and least deprived areas, respondents in the least deprived regions were more likely to drive a car to complete a journey than those living in more deprived areas, and a higher proportion of those living in the least deprived areas reported travelling the previous day compared to those in more deprived areas. There was also more awareness of EVs reported in the less deprived areas. Therefore, there are clear interactions between these key socioeconomic indicators and transport in Scotland.

3. Methodology

The research methodology falls into two distinct parts, dataset development and dataset analysis. The current section will detail each in turn. Section 3.1 outlines dataset development. As stated in the research questions detailed in Section 1, this paper seeks to understand what types of areas public EV chargers tend to be located in, when they tend to be used, how charging tariffs can impact utilisation of the chargers, and which characteristics the most utilised chargers possess. Raw EV charging-session data from ChargePlace Scotland can give general insights into when chargers are used and possible tariff impacts, but further information is needed to evaluate the types of areas where chargers are located and their associated characteristics. Therefore, Section 3.1 includes the collation and pre-processing of ChargePlace Scotland data, as well as the selection and inclusion of relevant additional data from the Urban–Rural Classification, Scottish Index of Multiple Deprivation, and Geographical Accessibility Index. Section 3.2 details the various dataset analysis processes, including the characterisation of public EV charger location distributions, exploration of trends in EV charging-session times, analysis of the impacts of charging tariffs, and investigation of the characteristics shared by the most utilised public EV chargers.

3.1. Dataset Development

Firstly, raw data from ChargePlace Scotland [30] that include every recorded EV-charging session taking place on the network between October 2022 and March 2024 were collated. For each session, the following information was extracted: the unique charge-point identification code for the charger on which the session took place; the start time and date of the session; the session duration; the energy consumed during the session; the local authority the charger is situated in; the postcode location of the charger; and the charger speed. It was assumed that each unique charge-point identification code represented a unique charger.

A number of data-cleansing measures were then undertaken to remove anomalous data entries. Specifically, sessions with a duration of 00:00:00, sessions including nulls, and sessions consuming 0 kWh were removed from the data. Additionally, sessions consuming greater than what would be compatible with the largest usable battery capacity currently available on the UK mass market [52] were removed. Furthermore, any charging sessions costing the user more than the most expensive tariff (plus the current overstay fee [53]) over a twenty-four-hour period were also removed. Anomalous data reporting was observed on some dates, namely 30 October 2022, 6 March 2023 to 12 March 2023 (inclusive), 5 June 2023 to 11 June 2023 (inclusive), 1 October 2023, and 4 February 2024, and so data for sessions on these dates were also removed. Local authority names were standardised, and where a charger was assigned different postcodes throughout the dataset time period, the most commonly appearing postcode was adopted as the unique charger location identifier. This same approach was taken for instances of a charger being assigned more than one charger speed.

To provide more context to the location of public EV chargers, the Urban–Rural Classification [54], the Scottish Index of Multiple Deprivation, and the Geographical Accessibility Index [55] were added to the dataset using geospatial techniques. As described in Section 2.2.3, the Urban–Rural Classification can give a clear indication for how urban or rural each charger's location is, and the Scottish Index of Multiple Deprivation and the Geographical Accessibility Index can provide a holistic understanding of how deprived and accessible each charger's location is, respectively. The addition of these indicators enriches the dataset, providing valuable additional contextual information with which to investigate the spatial distributions of existing EV public chargers. In order to add these additional indicators to the overall dataset, each charger was mapped using its postcode location. Spatial joining in ArcMap Version 10.8.2 [56] was then used to assign each charger its corresponding Urban–Rural Classification, Scottish Index of Multiple Deprivation, and Geographical Accessibility Index. Spatial joining allows data to be joined based upon their spatial locations [57]. Figure 3 provides a graphical summary of the dataset creation process.

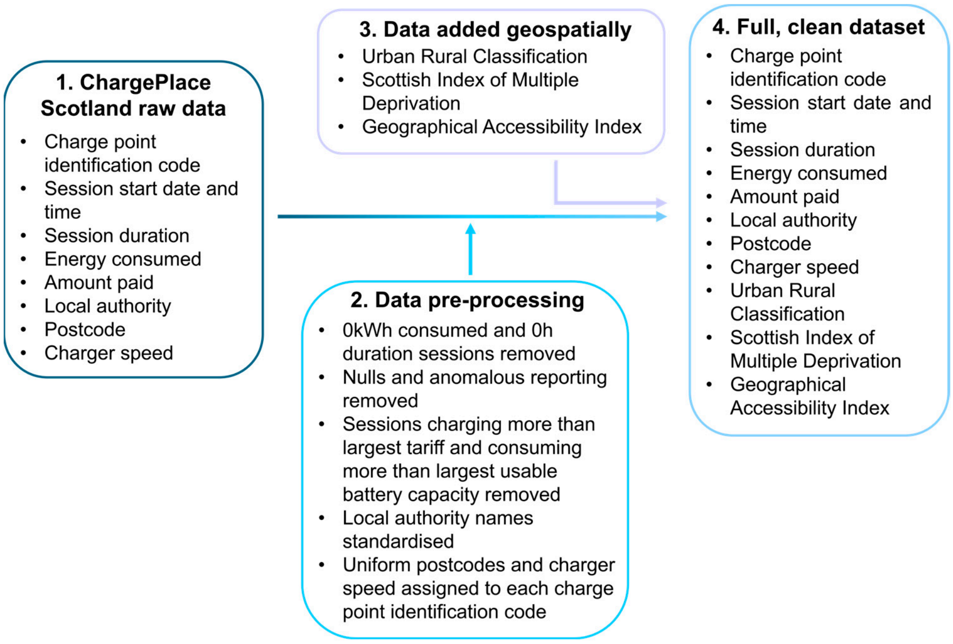

Figure 3. Flowchart outlining the dataset creation process, including cleansing of raw EV charging-session data from ChargePlace Scotland and the addition of supplementary geographical indicators.

3.2. Dataset Analysis

The dataset analysis falls into four categories, each addressing one of the research questions outlined in Section 1. Figure 4 details the four categories of dataset analysis and the analysis process that is related to each research question. A series of subsections will now provide a description of each analysis.

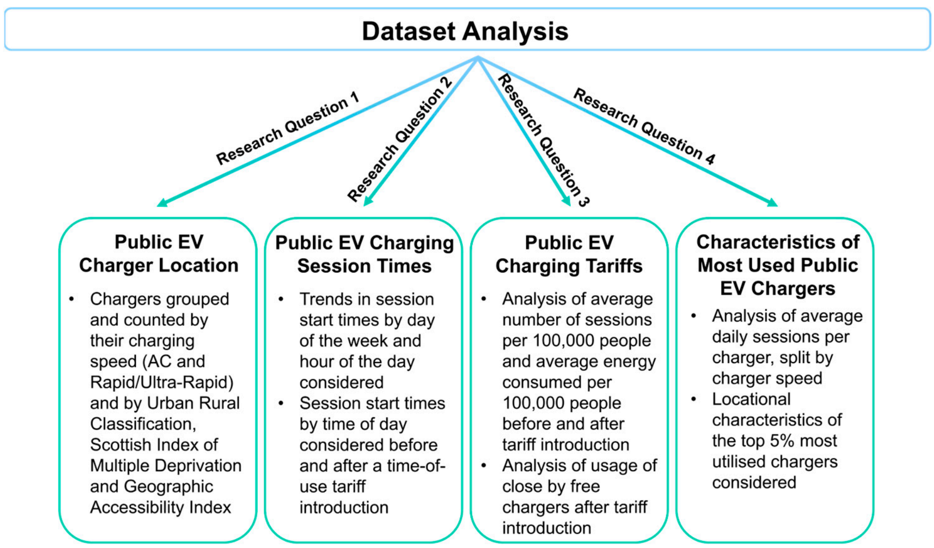

Figure 4. Flowchart detailing the dataset analysis processes conducted and their related research questions that they are conducted to address.

3.2.1. Public EV Charger Locations

To understand how public chargers on the ChargePlace Scotland network are spatially distributed, the number of chargers located in each Urban–Rural Classification and in each quintile of the Scottish Index of Multiple Deprivation and Geographical Accessibility Index was determined. The separation of the Scottish Index of Multiple Deprivation and Geographical Accessibility Index into quintiles is informed by Scottish Government guidance [58]. This allows for chargers to be grouped and labelled by the government-defined quintile of the Scottish Index of Multiple Deprivation and Geographical Accessibility Index that they are located in.

To also gain an understanding of the different types of EV-charging infrastructure located in each area type, the chargers were firstly split by their charging speed into two categories—'AC' and 'rapid/ultra-rapid'. Rapid and ultra-rapid chargers were combined, as there were only five ultra-rapid chargers contained in the dataset. Next, the chargers were grouped by their Urban–Rural Classification, Scottish Index of Multiple Deprivation quintile, and Geographical Accessibility Index quintile and counted so that the number of AC and rapid/ultra-rapid chargers in each location category is known.

3.2.2. Public EV Charging-Session Times

To understand when public EV chargers are generally used, weekday trends in the number of charging sessions taking place and trends in charging session start time are explored. Firstly, the average number of charging sessions taking place per day of the week was calculated for all sessions. This was also calculated for the subsets of sessions taking place in Urban–Rural Classification 1 and 8 areas, and for the first and fifth quintiles of the Scottish Index of Multiple Deprivation and Geographical Accessibility Index. In addition to the mean number of sessions taking place on each day of the week, the standard deviation was also calculated for each area type.

To explore trends in the time of day that charging sessions tend to start, the session data were split into sessions taking place on the weekends and on weekdays. The charging-session start time was then grouped into hourly brackets (e.g., from midnight to 1 a.m., from 1 a.m. to 2 a.m., from 2 a.m. to 3 a.m., etc.), and the number of sessions starting within each bracket was counted. Again, this was conducted for all charging sessions, as well as for the subsets of sessions in Urban–Rural Classification 1 and 8 areas and for the first and fifth quintiles of the Scottish Index of Multiple Deprivation and Geographical Accessibility Index. Charging-session start time was used as a proxy for the times when charging sessions tend to occur. Charging-session duration was not used, as it is difficult to delineate overstay behaviours within the data. This is particularly relevant to the developed dataset, as it features sessions that took place on some chargers that were free to use, meaning that there was no financial incentive to reduce overstay tendencies.

Charging-session start-time trends were also analysed before and after the introduction of time-of-use tariffs in East Lothian, as described in Section 2.2.1, as it was hoped that they would shift peak charging demand away from times of peak energy demand. Charging-session data for the week before and after the introduction date (1 March 2023) were excluded from the analysis to allow time for behavioural changes to settle. The average plug-in time and the total percentage of sessions starting during the time where the increased charging fee is active (i.e., from 4 p.m. to 8 p.m.) were calculated before and after the introduction of the time-of-use tariff programme. Additionally, a two-sample Kolmogorov–Smirnov statistical test [59] was conducted for session data before and after the tariff introduction to help ascertain whether any differences are statistically significant. A returned p-value of less than 0.05 indicates that the null hypothesis (this being that the two datasets are drawn from the same distribution) would be rejected at the 5% level. In such cases, the Kolmogorov–Smirnov test may be interpreted as confirming a statistically significant difference in the underlying distribution of the two datasets in question.

3.2.3. Public EV-Charging Tariffs

For the twelve Scottish local authorities that introduced EV-charging tariffs within the dataset time period (as described in Section 2.2.1), the average number of daily sessions per 100,000 people and average daily energy consumed per 100,000 people were calculated before and after tariff introduction. As with the East Lothian time-of-use tariff analysis described in Section 3.2.2, charging-session data from the week before and after the tariff introduction date were excluded from the analyses to allow time for behavioural changes to settle.

Additionally, a closer examination of tariff introduction in three local authorities, namely Perth and Kinross, North Lanarkshire, and Renfrewshire, was conducted to ascertain whether tariff introductions appear to push additional demand onto nearby free ChargePlace Scotland chargers. A ten-kilometre buffer was defined around the borders of these local authorities using ArcMap to identify chargers that are within this distance while being outside the local authorities themselves. Of the chargers identified, only those within local authorities that still offered free EV charging at the time a tariff was introduced in Perth and Kinross, North Lanarkshire, or Renfrewshire were analysed. The number of daily sessions experienced by these chargers was counted to understand if the impact of tariff introduction in these local authorities had an impact on the utilisation of neighbouring free chargers. For this analysis, it was assumed that all chargers were owned by the local authority they were situated in and so were bound by the terms of use set out by their respective local councils. As mentioned in Section 2.2, although there are multiple different charger operators on the ChargePlace Scotland network, chargers are predominantly owned and operated by local councils [14].

3.2.4. Characteristics of the Most Utilised Public EV Chargers

To gain an understanding of the utilisation of each public EV charger, the average number of daily charging sessions experienced by each charger was determined. Only charging sessions that were paid for (i.e., were not free) were included in this analysis to eliminate the impacts of the charging tariff's introduction.

The total number of charging sessions that took place for each charger was counted, and this was then divided by the total number of days each charger was active. When determining the number of days that a charger was active, one must account for instances where a charger was taken offline before the end of the dataset. The number of days active was therefore determined as follows. First, the date of the first recorded session for each charger was found. The date of the last recorded session for each charger was then also found, and the average number of days between charging sessions determined for each charger. If the number of days between the last recorded session of a charger and the last date of the dataset (31 March 2024) was greater than the average number of days that charger experiences between sessions, then the last active date of the charger was assumed to be its last recorded session date plus the average number of days that charger experiences between sessions. Otherwise, if the number of days between the last recorded session of a charger and the last date of the dataset was less than the average number of days that charger experiences between sessions, then the last active date of the charger was assumed to be the last date of the dataset. The total number of days active was then calculated as the number of days between the first recorded session of a charger and its last active date. It was assumed that each charger was not active before its first recorded session.

The chargers were then split by their charger speed (i.e., AC vs. rapid/ultra-rapid) so that the utilisation of chargers of each speed could be considered separately. The top five percent most utilised chargers (determined from the average number of daily sessions) were then isolated and grouped according to their locational characteristics (i.e., Urban–Rural Classification, Scottish Index of Multiple Deprivation, and Geographical Accessibility Index) to allow for any commonalities to be identified.

3.3. Limitations

There are limitations associated with the above research methodology. Firstly, although measures were taken to improve data quality, as described in Section 3.1, errors and inaccuracies may remain. For example, charge-point identification codes could change or be reassigned to different chargers throughout the dataset time period, and not all chargers available on the ChargePlace Scotland network are guaranteed to be represented in the dataset. Additionally, the geospatial plotting of the chargers by postcode, also described in Section 3.1, carries some limitations. Each charger's location was necessarily interpreted as the centroid of its associated postcode; however, this may not match the exact location of the charger, meaning that the plotted charger location may be inaccurate in some cases [60]. Furthermore, postcodes in general can change and be reassigned elsewhere, and postcodes tend to cross other boundary types, such as electoral wards and health boards [61]. Therefore, there may be some instances of incorrectly allocated data when using the described geospatial techniques.

As mentioned in Section 3.2.3, it is assumed that all chargers were local authority-owned for the analysis regarding the impact of tariff introduction on neighbouring free chargers. However, it is possible that some chargers included in this analysis were not owned by the local authority or free to use. For the analysis outlined in Section 3.2.4, as stated, it was assumed that a charger's first recorded session was its first active date as a charger that was not free to use. However, it is possible that the charger was active (and not free to use) prior to the date of its first recorded session. Therefore, the process outlined above for estimating the last active date may contain small inaccuracies for some chargers. Additionally, this analysis uses only charging sessions that were paid for in order to eliminate impacts of tariff introduction; however, this means that chargers that were free to use for the entirety of the dataset time period (e.g., chargers owned by North, East, and South Ayrshire council) are not included in the analysis. These limitations should be considered when interpreting the results.

The Scottish Index of Multiple Deprivation, its Geographical Accessibility Index element, and the Urban–Rural Classification also have associated limitations. The Scottish Index of Multiple Deprivation, further described in Section 2.2.3, can give a holistic understanding of deprivation at a detailed level, but it cannot give an indication of affluence [62]. It is also designed to identify deprived areas, not deprived individuals. For example, more than 50% of people classified as having a low income do not reside in areas falling within the most deprived quintile of the Scottish Index of Multiple Deprivation [63]. There are also particular limitations with respect to rural areas, where deprivation is more widely scattered across a larger area and individual data zones are tasked with capturing a larger blend of deprived and less deprived households [64,65]. In terms of the Urban–Rural Classification, limitations include small towns being considered more urban than rural, which may not always be accurate, and a lack of representation of the challenges experienced by island communities [50]. The limitations of these indicators should be kept in mind when considering the results of the analyses which include them.

4. Results and Discussion

To understand how public EV chargers are currently used and distributed in Scotland, a dataset containing charging-session data was developed, as detailed in Section 3. The following subsections outline and discuss the results of the analysis of this dataset, including an overview of the dataset itself, as well as utilisation and location findings. The implications of these results will be discussed in Section 5.

4.1. Dataset Overview

Table 1 details the number of charging sessions and unique chargers included in the dataset before and after the data pre-processing measures described in Section 3.1 were taken. The number of sessions after data-cleaning procedures taking place in Urban–Rural Classifications 1 and 8, and the number of charging sessions falling within the first and fifth quintiles of the Scottish Index of Multiple Deprivation and Geographical Accessibility Index are also reported as these are used in some analyses. Furthermore, the number of charging sessions that were paid for (i.e., not free) is also reported, as this is used in the analysis surrounding the characteristics of the most utilised chargers, detailed in Section 3.2.4. Table 1 shows that 86.7% of all sessions were retained after data cleaning and, considering splits between the socioeconomic indicators, there are clear disparities in the number of sessions and chargers across the different Urban–Rural Classifications and Scottish Index of Multiple Deprivation and Geographical Accessibility Index quintiles considered, which is important to bear in mind when considering some results.

Table 1. Overview of the number of EV-charging sessions included in the dataset before and after data-cleansing procedures, and of the number of sessions taking place in the different locational categories considered in some analyses.

Type of Charging Sessions	Number of Charging Sessions	Number of Unique Chargers
All sessions before data cleansing	3,120,526	3543
All sessions after data cleansing	2,705,585	2786
Urban–Rural Classification 1 sessions	885,965	809
Urban–Rural Classification 8 sessions	81,323	201
Scottish Index of Multiple Deprivation 1st quintile sessions	567,517	525
Scottish Index of Multiple Deprivation 5th quintile sessions	485,238	377
Geographical Accessibility Index 1st quintile sessions	430,052	621
Geographical Accessibility Index 5th quintile sessions	870,716	794
Paid for sessions	1,514,981	2426

Additionally, 77% of the chargers in the dataset were found to be AC chargers, with the remaining 23% being rapid/ultra-rapid chargers. Figure 5 gives an overview of the total number of charging sessions taking place on the ChargePlace Scotland network across the dataset time period and the number of chargers observed across the same time period. Interestingly, this shows a slightly decreasing trend in the number of sessions taking place, while the number of chargers increases. This observation will be revisited in Section 5. There are also notable dips in the number of sessions across the festive period surrounding Christmas and New Year.

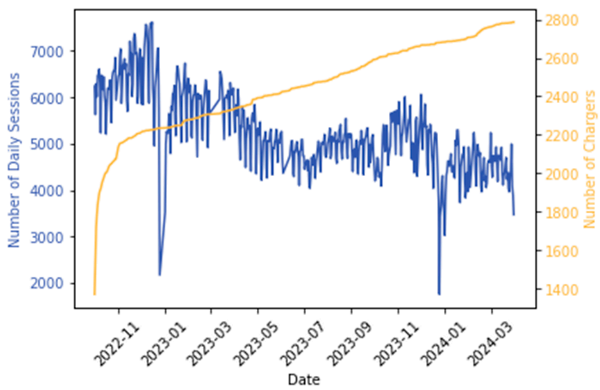

Figure 5. The total number of EV-charging sessions taking place on the ChargePlace Scotland public network between October 2022 and March 2024.

4.2. Public EV Charger Location

Exploring where chargers on the ChargePlace Scotland network are currently located can help identify how equitably distributed chargers are depending on different area types.

Figure 6 shows the absolute number of AC and rapid/ultra-rapid chargers in each Urban–Rural Classification within the constructed dataset, and Figure 7 shows the number of AC and rapid/ultra-rapid chargers per 100,000 people in each Urban–Rural Classification. Note that there are disparities in the populations falling within each Urban–Rural Classification (e.g., Urban–Rural Classification 1 has a population of over 2 million people, while Urban–Rural Classification 8 has a population of around 151,000 people [66]), resulting in varying trends between the absolute number of chargers and the number of chargers per 100,000 people. This observation will be revisited in Section 5.

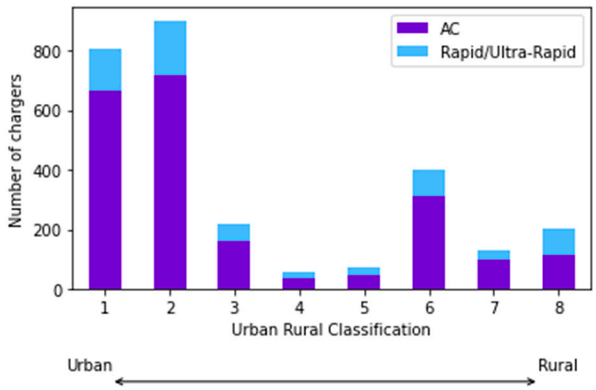

Figure 6. The absolute number of EV chargers on the ChargePlace Scotland public network found in each Urban–Rural Classification, where a lower classification value generally indicates a more urban area, and a higher value generally indicates a more rural area.

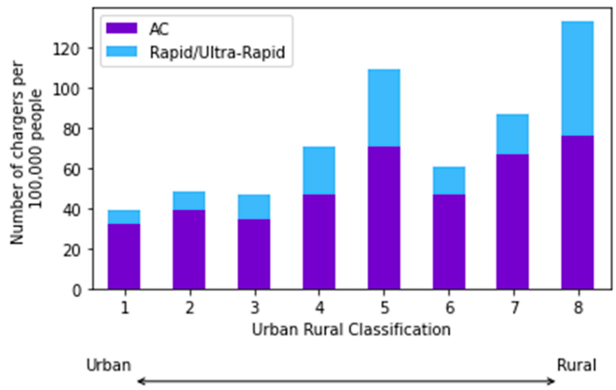

Figure 7. The number of EV chargers per 100,000 people on the ChargePlace Scotland public network found in each Urban–Rural Classification, where a lower classification value generally indicates a more urban area, and a higher value generally indicates a more rural area.

Figure 6 shows that the absolute number of chargers is generally concentrated in more urban areas. There are 1929 chargers in total in urban areas (i.e., where the Urban–Rural Classification is less than or equal to 3) and 857 chargers in total in rural areas (i.e., where the Urban–Rural Classification is greater than or equal to 4). Urban–Rural Classification 2 has the greatest number of chargers, hosting 900 in total, while Urban–Rural Classification 4 has the least number of chargers, with just 56 in total. In all Urban–Rural Classifications, there are more AC chargers than rapid/ultra-rapid chargers.

However, Figure 7 shows that, when normalised by population, the charger density is skewed in favour of rural populations. In this context, Urban–Rural Classification 8 has the highest density of chargers, with approximately 133 chargers per 100,000 people, and Urban–Rural Classification 1 has the fewest chargers, with circa 39 chargers per 100,000 people. This demonstrates that although the absolute number of chargers tends to be higher in urban areas, rural areas have a higher number of chargers per head of population. However, given that rural communities may be more likely to be spread across large areas, it is possible that chargers are difficult to reach for these communities despite their relatively high number per 100,000 people. Additionally, as mentioned in Section 2.2.3, people living in rural areas are more likely to make journeys by car and less likely to have or use alternative modes (e.g., public transport) [51]. Therefore, these communities may be more likely to be dependent on cars, so ensuring there is sufficient public charging infrastructure will be important in supporting the electrification of private cars. Again, there are generally more AC chargers (per 100,000 people) than rapid/ultra-rapid chargers in each Urban–Rural Classification. Urban–Rural Classification 8 has the most even split, with circa 76 AC chargers (per 100,000 people) and circa 57 rapid/ultra-rapid chargers. A higher proportion of rapid/ultra-rapid chargers in more rural areas may be important, as these areas could require more charging to complete journeys since people here tend to travel further daily distances compared to their urban counterparts [51], as mentioned in Section 2.2.3.

Figures 8 and 9 give the number of chargers found in each quintile of the Scottish Index of Multiple Deprivation and Geographical Accessibility Index, respectively. The population across the quintiles of both indicators is relatively similar (there was a difference of 9% between the population in the most and least populous Scottish Index of Multiple Deprivation quintiles, and there was a difference of 4% between the population in the most and least populous Geographical Accessibility Index quintiles). Therefore, the trends in the absolute number of chargers and the number of chargers per 100,000 people for these indicators are similar. Plots of the number of chargers per 100,000 people are given in Appendix A for completeness.

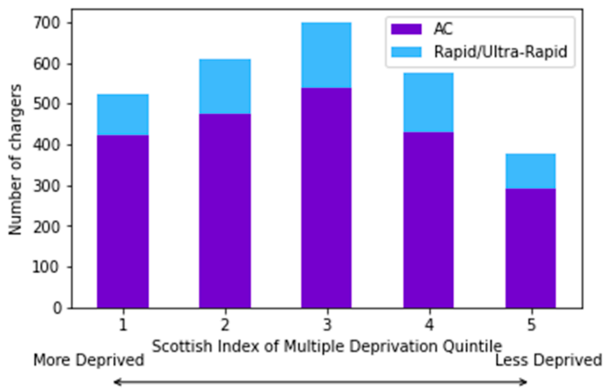

Figure 8. The absolute number of EV chargers on the ChargePlace Scotland public network found in each Scottish Index of Multiple Deprivation quintile, where a lower quintile generally indicates a more deprived area, and a higher quintile generally indicates a less deprived area.

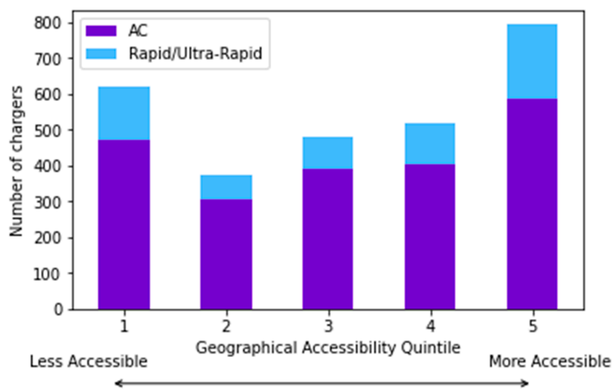

Figure 9. The absolute number of EV chargers on the ChargePlace Scotland public network found in each Geographical Accessibility Index quintile, where a lower quintile generally indicates a less accessible area, and a higher quintile generally indicates a more accessible area.

The total number of chargers across the Scottish Index of Multiple Deprivation quintiles varies, with the third quintile (areas falling within the 60% most deprived in Scotland) having the greatest number of chargers, with 698 in total, and the fifth (least deprived) quintile having the smallest number of chargers, with 377 in total—almost half of that in the third quintile. The first, second, and fourth quintiles have relatively similar numbers of chargers, with 525, 609, and 577 chargers, respectively. The least deprived quintile having the fewest number of chargers suggests that public EV chargers on the ChargePlace Scotland network do not seem to be disproportionately concentrated in less deprived communities, thus offering positive implications concerning an equitable transition to EVs. Indeed, the observed disparities in the number of chargers located in more versus less deprived areas appear to be less severe than what is seen in other areas, according to trends found in previous works [5,8], mentioned in Section 1, that find that public charging infrastructure is disproportionately concentrated in the least deprived areas. It is, however, important to note that Scotland may face different socioeconomic challenges and complexities compared to the geographical focuses of these previous works; hence, the specific reason for this more positive distribution of chargers is not currently known.

There is slightly more variation in the number of chargers across the Geographical Accessibility Index quintiles. The most accessible quintile has the greatest number of chargers, containing 794 chargers, followed by the least accessible quintile, which contains 621 chargers. The second quintile has the lowest number of chargers (374 in total), followed by the third and fourth quintiles, which have 479 and 518 chargers, respectively. Again, the least accessible quintile having the second largest number of chargers has a positive implication for enabling an equitable transition; however, EV drivers in these less accessible areas may be driving farther to reach these chargers. As a case in point, chargers in Dundee City council had the highest value for the Geographical Accessibility Index (were rated most accessible) on average, and this local authority spans 60 square kilometres in area [67]. Meanwhile, Na h-Eileanan Siar council chargers had the lowest value for the Geographical Accessibility Index (were rated least accessible) on average, and this local authority spans a much greater area of 3059 square kilometres [67] in comparison to Dundee City. Therefore, the least accessible areas may require significantly more chargers than the most accessible areas to achieve parity. Ensuring that less accessible areas have sufficient access to public charging will be paramount for an equitable transition to EVs; however, it will also be important to ensure that the middle quintiles do not get left behind as the charging network expands.

Therefore, in relation to research question 1 (concerning where public EV chargers are currently located), our analysis of the developed dataset reveals that public EV chargers on the ChargePlace Scotland network tend to be situated mostly in urban areas, while, simultaneously, rural areas tend to have more chargers per head of population. More deprived areas also tend to have more chargers than areas deemed less deprived, according to the Scottish Index of Multiple Deprivation. Finally, the top 20% most geographically accessible areas had the most chargers; however, this was closely followed by the 20% least accessible areas. Overall, these findings suggest that the current spatial distribution of the ChargePlace Scotland network is a good starting point for a continued equitable transition to EVs, with Scotland appearing to deviate from trends found in other countries where charging infrastructure tends to be focused in the least deprived areas.

4.3. Public EV Charging-Session Times

Understanding when chargers on the ChargePlace Scotland network are currently used, specifically trends in the day of the week that charging sessions take place and the time of day that charging sessions start, can identify times of high demand for charging network infrastructure.

Figure 10 shows the average number of sessions per 100,000 people taking place on each day of the week for all sessions in the dataset, as well as for sessions facilitated by chargers in Urban–Rural Classification 1 and 8 areas, and in first and fifth quintiles of the Scottish Index of Multiple Deprivation and Geographical Accessibility Index. Each plot shows the mean number of sessions (per 100,000 people) occurring on each day of the week for each area type, plus and minus one standard deviation.

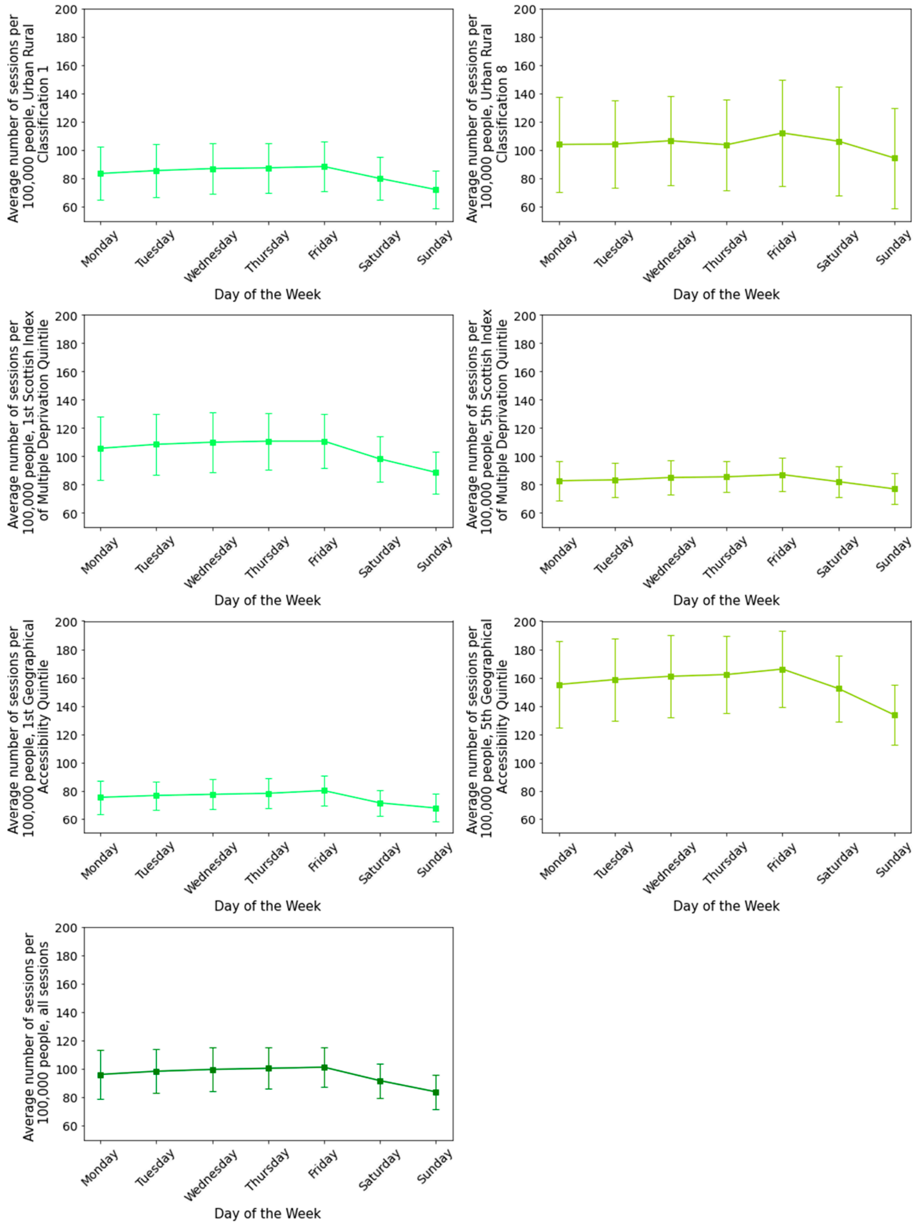

Figure 10. The average number of sessions taking place each day of the week on the ChargePlace Scotland public EV-charging network for all areas and for Urban–Rural Classification 1 and 8 areas and first and fifth quintiles of the Scottish Index of Multiple Deprivation and Geographical Accessibility Index areas.

The trends in average sessions by day of the week generally show that weekends have slightly fewer sessions per 100,000 people than weekdays; however, the trend is less clear for Urban–Rural Classification 8 and the fifth quintile of the Scottish Index of Multiple Deprivation. In Urban–Rural Classification 8, the average number of sessions on a Saturday is more in line with values found for weekdays, and in the fifth quintile of the Scottish Index of Multiple Deprivation, the decrease in sessions on the weekends appears less significant compared to other areas.

For all locational categories considered, Friday had the most sessions per 100,000 people on average, with 101 sessions (per 100,000 people) for all sessions in the dataset; 111 and

87 sessions for the first and fifth Scottish Index of Multiple Deprivation quintiles, respectively; 80 and 166 sessions for the first and fifth Geographical Accessibility Index quintiles, respectively; and 88 and 112 sessions for Urban–Rural Classifications 1 and 8, respectively. This may be because, as mentioned in Section 2.2.3, most journeys tend to occur on a Friday, according to the Scottish Household Survey [51]. Meanwhile, Sunday had the least sessions per 100,000 people on average for all area types, with 84 sessions (per 100,000 people) for all sessions in the dataset; 89 and 77 sessions for the first and fifth Scottish Index of Multiple Deprivation quintiles, respectively; 68 and 134 sessions for the first and fifth Geographical Accessibility Index quintiles, respectively; and 72 and 94 sessions for Urban–Rural Classifications 1 and 8, respectively.

Interestingly, the fifth quintile of the Geographical Accessibility Index tends to have more daily sessions per 100,000 people on average compared to the other areas considered, and Urban–Rural Classification 8 features the most variation, as evidenced by the larger standard deviations compared to the other area types. The general trend of fewer sessions on average on weekends suggests that as EV adoption and utilisation of the public charging network increases, it may become important to incentivise charging on weekends to reduce pressure at busier times. However, the disparities in trends across the different locational characteristics indicate that a localised approach may be necessary, which is supported by other studies that find that different areas will have different public charging needs [23,24].

Figure 11 shows the trends in the time of day that charging sessions tend to start on weekdays and weekends for all sessions included in the dataset and also for those occurring in Urban–Rural Classification 1 and 8 areas.

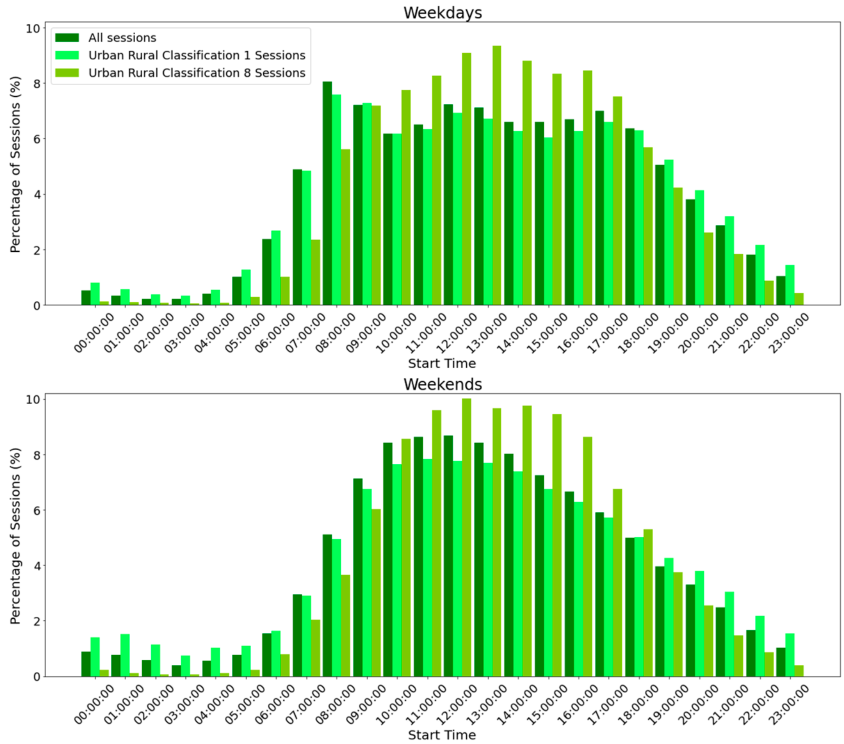

Figure 11. Trends in start time of charging sessions on the ChargePlace Scotland public EV-charging network for all sessions, and sessions in Urban–Rural Classifications 1 and 8.

As illustrated by Figure 11, the overall trend for all sessions during the week is reflective of a traditional nine-to-five schedule. There are peaks in charging-session start time between 8 a.m. and 10 a.m., which could be thought of as a pre-work peak, a lunchtime peak between 12 noon and 2 p.m., and a post-work peak between 5 p.m. and 6 p.m. These trends in session start time tend to align with times of peak energy demand in the UK [68], with 84.4% of sessions taking place between 8 a.m. and 9 a.m. Therefore, in the future, it may become important to influence charging behaviour and encourage sessions to start at off-peak times. The overall trend for all sessions on the weekends is reflective of the more relaxed schedule many enjoy on Saturdays and Sundays, with activity mainly concentrated towards the middle of the day and peaking at 12 noon. Specifically, 42.2% of all sessions started between 10 a.m. and 3 p.m. on weekends.

As shown in Figure 11, Urban–Rural Classification 1 session start-time trends are generally similar to the overall trends found for all charging sessions in the dataset. However, Urban–Rural Classification 1 chargers tend to have slightly more sessions taking place overnight compared to trends for all sessions, particularly on the weekends. For example, 9.1% of all sessions started between 9 p.m. and 6 a.m. on the weekends compared to 13.97% of sessions in Urban–Rural Classification 1 areas. There also tend to be slightly fewer sessions in Urban–Rural Classification 1 areas starting towards the middle of the day during weekends—38.3% of sessions started between 10 a.m. and 3 p.m. here.

However, Urban–Rural Classification 8 areas show a different trend for charging-session start times. On both weekends and weekdays here, sessions tend to start more towards the middle of the day, peaking at 1 p.m. on weekdays and 12 noon on weekends. Specifically, 43.8% of sessions in Urban–Rural Classification 8 areas take place between 11 a.m. and 4 p.m. on weekdays, and 48.5% take place between 11 a.m. and 4 p.m. on weekends (compared to 34.1% and 41%, respectively, for all sessions). This further emphasises that urban and rural areas in Scotland tend to feature different charging behaviours and therefore may require different approaches to adequately meet public charging needs.

Figure 12 shows the session start-time trends for all sessions and also for those occurring in the first and fifth quintiles of the Scottish Index of Multiple Deprivation. Additionally, Figure 13 shows the session start-time trends for all sessions and for those occurring in the first and fifth quintiles of the Geographical Accessibility Index. The trends across the first and fifth quintiles of both indicators are similar to the overall trends for all sessions. The trends for the first (most deprived) quintile of the Scottish Index of Multiple Deprivation feature a higher proportion of nighttime sessions on the weekends, with 12% starting between 9 p.m. and 6 a.m. Meanwhile, the first (least accessible) quintile of the Geographical Accessibility Index tends to have slightly more sessions concentrated towards the middle of the day on the weekends, with 43.1% starting between 11 a.m. and 4 p.m. Interestingly, although fewer sessions take place overnight in the first (least accessible) quintile of the Geographical Accessibility Index compared to the overall trend, the difference is not as great as that between the most rural areas and the overall trend. Specifically, in the first quintile of the Geographical Accessibility Index, 7.1% of sessions occur between 9 p.m. and 6 a.m. on weekends, and 7.3% occur on weekdays, compared to 9.1% for all sessions on weekends and 8.4% on weekdays. In the most rural areas (as shown in Figure 11), 3.5% of sessions occur between 9 p.m. and 6 a.m. on weekends, and 3.8% on weekdays. This difference is likely because the Urban–Rural Classification and Geographical Accessibility Index capture different aspects of accessibility/remoteness. As outlined in Section 2.2.3, the Urban–Rural Classification gives a standardised definition of how urban or rural an area is depending on its population and/or distance to communities of certain population thresholds. Meanwhile, the Geographical Accessibility Index captures accessibility through incorporating information on access to public and private transportation and access to physical and digital services. Therefore, the Geographical Accessibility Index captures accessibility/remoteness more in terms of access to services, whilst the Urban–Rural Classification captures accessibility/remoteness more in terms of population structures, and so different behaviours are observed.

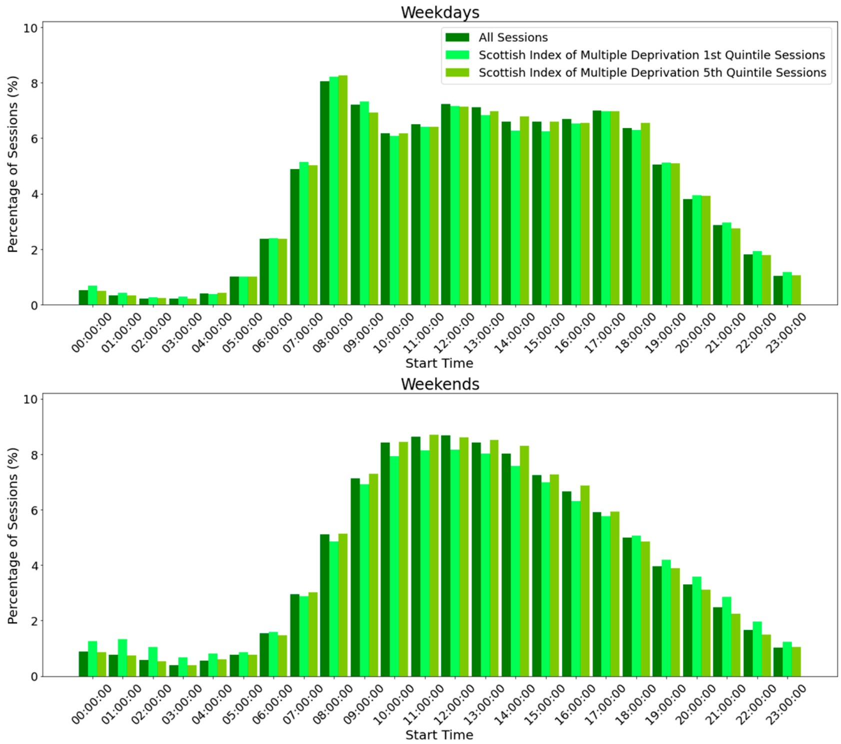

Figure 12. Trends in start time of charging sessions on the ChargePlace Scotland public EV-charging network for all sessions, and sessions in first and fifth Scottish Index of Multiple Deprivation quintiles.

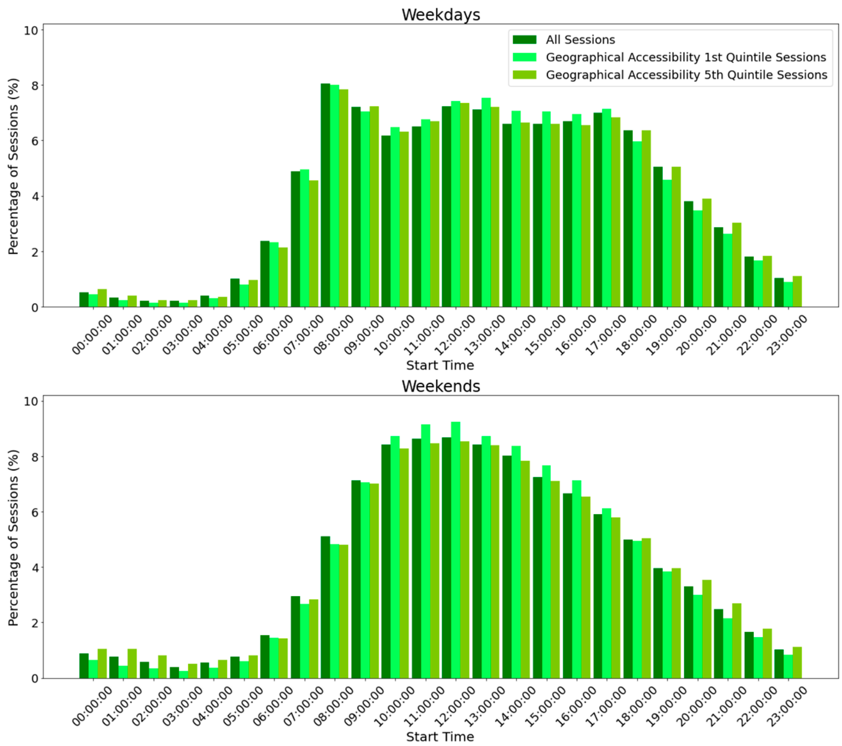

Figure 13. Trends in start time of charging sessions on the ChargePlace Scotland public EV-charging network for all sessions, and sessions in first and fifth Geographical Accessibility Index quintiles.

As mentioned in Section 2.1, time-of-use tariffs have been proposed as a means to shift charging-time behaviour. To explore the impact that time-of-use tariffs have on the average charging-session start time, data for chargers included in the East Lothian trial of this type of tariff programme (as described in Section 2.2.1) were considered. Figure 14 shows the trends in charging-session start time before and after implementation of the time-of-use tariff, including a vertical black dotted line indicating the average session start time or 'plug-in' time.

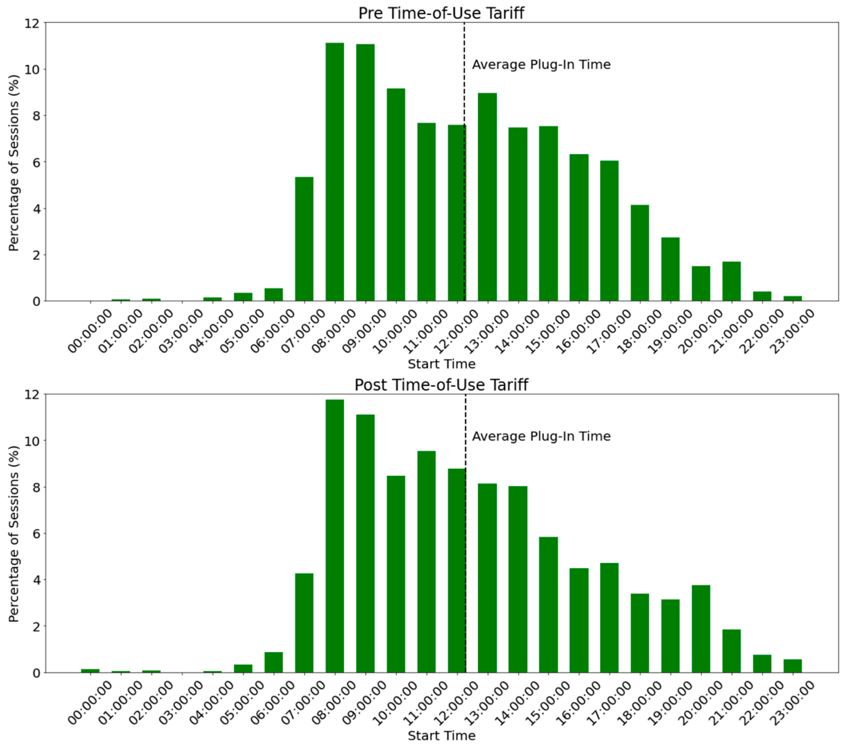

Figure 14. Trends in start time of charging sessions for nine chargers in East Lothian on the ChargePlace Scotland public EV-charging network before and after introduction of a time-of-use tariff, with the average plug-in time marked by a vertical black dotted line.

Before the time-of-use tariff implementation, 19.2% of sessions started between 4 p.m. and 8 p.m. (the times that the increased fee is active). After introducing the new tariff programme, there was a decrease in the proportion of sessions starting in this time bracket, with 15.7% of sessions starting between 4 p.m. and 8 p.m. The result of the two-sample Kolmogorov–Smirnov test gave a p-value of 0.02, indicating that the difference observed is statistically significant at the 5% level, as described in Section 3.2.2. This suggests that there may be potential for shifting the demand using time-of-use tariff schemes. However, the average session start time remained relatively unchanged before and after the introduction of the time-of-use tariff—prior to the new tariff programme, the average plug-in time was 12:24 p.m., and, afterwards, this shifted forwards slightly to 12:28 p.m.

Additionally, this analysis is relatively small-scale. Only twelve ChargePlace Scotland chargers were involved in the time-of-use tariff trial, and of those twelve chargers, data for nine were included in the dataset and the subsequent analysis. Furthermore, the chargers were all located in one local authority area, and the trial time period is relatively short. Specifically, there were five months of data (2907 charging sessions) to consider before the time-of-use tariff introduction and one year of data (5903 charging sessions) to consider after the time-of-use tariff's introduction.

Therefore, in relation to research question 2 (concerning when public EV chargers tend to be used), our analysis of the developed dataset found that chargers on the ChargePlace Scotland network tend to be used more during weekdays than weekends in general; however, different area types experience this trend to different degrees. Furthermore, on weekdays, the charging start time generally tends to follow a nine-to-five-style pattern, while weekends feature charging-session start-time activity concentrated more towards the middle of the day. Similarly, there are disparities between different area types, with Urban–Rural Classification 8 specifically exhibiting charging start times more concentrated towards the middle of the day on weekdays also. Time-of-use tariffs appear to have potential to facilitate some demand shifting away from peak times; however, more data/cases would be required to more fully demonstrate and quantify this.

4.4. Impact of Public EV-Charging Tariffs on Utilisation

As described in Section 2.2.1, twelve local authorities introduced tariffs during the dataset time period. Table 2 shows the changes in the average number of daily sessions per 100,000 people and average daily energy consumed per 100,000 people for the relevant twelve local authorities, both before and after tariff introduction. The reductions in average daily sessions per 100,000 people range from 77% (in Clackmannanshire) to 19.5% (in West Dunbartonshire), and the decreases in average daily energy consumed per 100,000 people range from 76.5% (in Clackmannanshire) to 1.9% (in West Dunbartonshire). The introduction of tariffs resulted in an average decrease of 51.3% in the number of daily sessions per 100,000 people and an average decrease of 50.0% in the average daily energy consumed per 100,000 people.

The date on which local authorities introduced tariffs for the chargers they own is also given in Table 2, and it should be noted that disparities in tariff introduction dates result in disparities in the number of data available before and after tariff introduction across the local authorities considered. This should be considered when interpreting these results, particularly in the case of South Lanarkshire, where the tariff was introduced in early November, just one month into the dataset time period. Additionally, when considering the results in Table 2, it is important to bear in mind that the tariff introduction date applies only to chargers owned and operated by the local council, and there may be other chargers within the local authority that have other owners and that are therefore subject to different tariff programmes.

By way of example, Figures 15–17 show plots of the number of sessions taking place in Dundee City, North Lanarkshire, and East Renfrewshire, respectively, as well as the number of chargers in each area. Dundee City already had a tariff in place before the beginning of the dataset time period, and the trends in the number of sessions taking place across the time frame are relatively stable. However, for North Lanarkshire and East Renfrewshire, steep declines in the number of sessions can clearly be seen around the time of tariff introduction (the date of which is marked on these plots by a vertical black dotted line). It is possible that tariff introduction across different local authorities has contributed to the decreasing trend in the overall number of sessions on the ChargePlace Scotland network demonstrated in Figure 5.

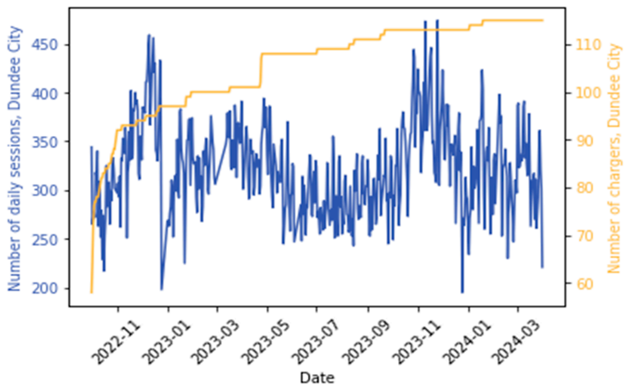

Figure 15. The number of sessions taking place in Dundee City, along with the number of chargers observed. Dundee City already had a tariff in place during this time period.

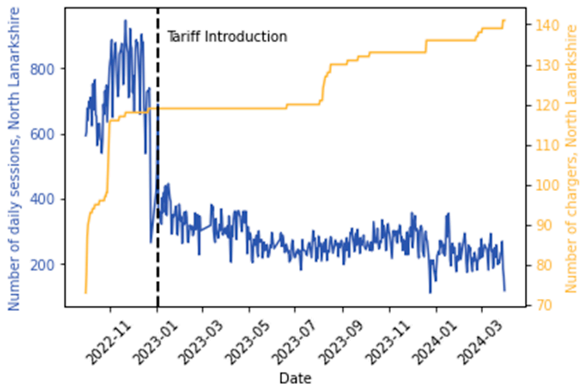

Figure 16. The number of sessions taking place in North Lanarkshire, along with the number of chargers observed. North Lanarkshire introduced a tariff on 4 January 2023, illustrated by the vertical black dotted line.

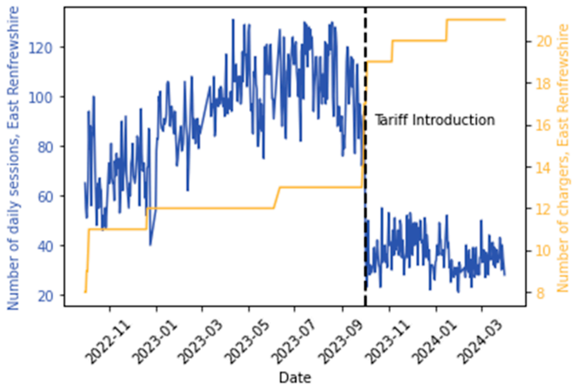

Figure 17. The number of sessions taking place in East Renfrewshire, with the number of chargers observed. East Renfrewshire introduced a tariff on 1 October 2023, illustrated by the vertical black dotted line.

The reduction in charger utilisation after tariff introduction indicates that when charging is free, there are two broad user groups—those who require the use of the public EV-charging network (those without access to residential or workplace charging facilities or who need to charge to complete a journey) and those who do not need to use the public network but choose to because of the financial incentive. Therefore, the charging demand post-tariff introduction may be more representative of the 'real' demand, as those who can charge privately will likely choose to do so, as this is typically cheaper and more convenient than charging publicly once a tariff is applied [69].

Table 2. The average number of daily sessions per 100,000 people and average daily energy consumed per 100,000 people before and after tariff introduction, with percentage differences, for the twelve local authorities that introduced tariffs throughout the dataset time period.

Local Authority (Tariff Introduced)	Average Number of Daily Sessions per 100,000 People (Sessions/100,000 People)			Average Daily Energy Consumed per 100,000 People (kWh/100,000 People)		
	Pre-Tariff	Post-Tariff	Percentage Change (%)	Pre-Tariff	Post-Tariff	Percentage Change (%)
Clackmannanshire (1 July 2023) [70]	242.2	54.0	−77.7	5369.1	1261.9	−76.5
East Dunbartonshire (2 October 2023) [71]	85.4	38.6	−54.8	1999.3	895.8	−55.2
East Renfrewshire (1 October 2023) [72]	96.1	37.6	−60.9	2380.7	903.8	−62.0

Table 2. *Cont.*

Local Authority (Tariff Introduced)	Average Number of Daily Sessions per 100,000 People (Sessions/100,000 People)			Average Daily Energy Consumed per 100,000 People (kWh/100,000 People)		
	Pre-Tariff	Post-Tariff	Percentage Change (%)	Pre-Tariff	Post-Tariff	Percentage Change (%)
Glasgow City (11 April 2023) [73]	108.4	49.5	−54.3	2390.0	963.7	−59.7
North Lanarkshire (4 January 2023) [74]	216.9	78.8	−63.7	4851.8	1699.8	−65.0
Perth and Kinross (1 January 2023) [75]	256.1	125.7	−50.9	5260.8	2426.0	−53.9
Renfrewshire (1 April 2023) [76]	198.0	95.0	−52.0	4010.3	1831.9	−54.3
Shetland Islands (11 April 2023) [77]	193.0	74.4	−61.4	3232.9	1519.4	−53.0
South Lanarkshire (1 November 2022) [78]	90.0	70.0	−22.2	1894.6	1586.9	−16.2
Stirling (1 February 2023) [79]	481.6	276.5	−42.6	10,074.1	5692.9	−43.5
West Dunbartonshire (1 June 2023) [80]	90.1	72.6	−19.5	1542.7	1512.9	−1.9
West Lothian (1 February 2023) [81]	159.5	71.8	−55.0	3412.9	1397.2	−59.1

It is also pertinent to consider the possible impacts of tariff introductions on neighbouring free chargers. Figures 18–20 show the number of daily sessions taking place on chargers within 10 km of North Lanarkshire, Renfrewshire, and Perth and Kinross borders (respectively) that were free to use at the time these local authorities introduced charging tariffs. The date that each local authority introduced tariffs for their chargers is marked on each plot with a vertical black dotted line.

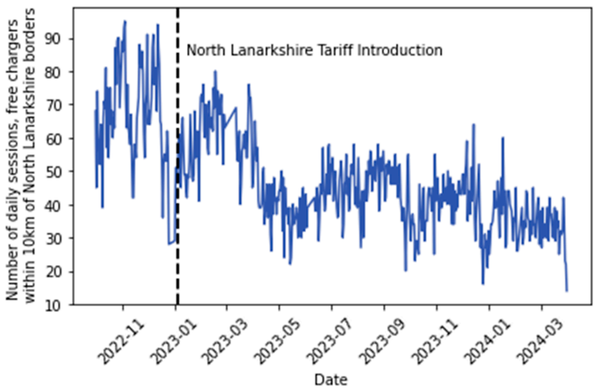

Figure 18. The number of sessions taking place on chargers within 10 km of North Lanarkshire borders that were free to use at the time of charging tariff introduction for North Lanarkshire council-owned chargers (the date of tariff introduction is represented by the vertical black dotted line).

Figures 18–20 indicate that the introduction of a tariff does not appear to significantly shift demand to nearby free chargers. It may, therefore, be that the majority of demand is instead shifting to private charging (e.g., workplace or residential chargers) when a tariff is introduced. As mentioned in Section 1, most EV drivers currently have access to residential charging [4]. Therefore, it is possible that a different effect may be observed as EV adoption reaches further into markets of consumers without home charging capabilities.

In relation to research question 3 (concerning the impact of the introduction of tariffs on usage of chargers), analysing the developed dataset found that introducing a tariff appears to significantly impact charger utilisation, reducing the number of sessions and energy consumed by chargers by around 50%. However, the available data indicate that the introduction of tariffs does not seem to have a significant impact on the utilisation of nearby chargers that remain free to use.

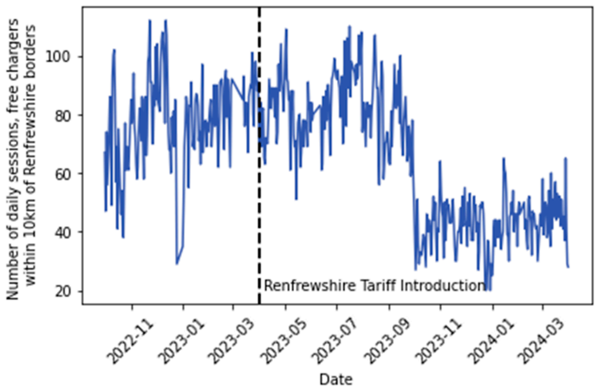

Figure 19. The number of sessions taking place on chargers within 10 km of Renfrewshire borders that were free to use at the time of charging tariff introduction for Renfrewshire council-owned chargers (the date of tariff introduction is represented by the vertical black dotted line).

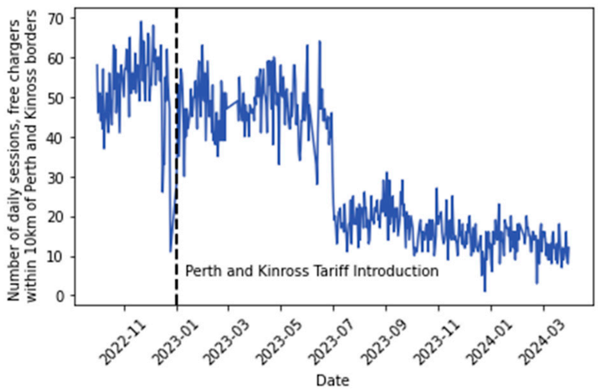

Figure 20. The number of sessions taking place on chargers within 10 km of Perth and Kinross borders that were free to use at the time of charging tariff introduction for Perth and Kinross council-owned chargers (the date of tariff introduction is represented by the vertical black dotted line).

4.5. Characteristics of the Most Utilised Chargers

The average number of daily sessions experienced by chargers in the dataset ranges from 0.002 to 5.3 sessions for AC chargers and from 0.06 to 12.9 sessions for rapid/ultra-rapid chargers. As shown in Figure 21, 35% of AC chargers are used on average at least once a day, compared to 86% of rapid/ultra-rapid chargers. On average, AC chargers experienced 0.9 daily sessions, and rapid/ultra-rapid chargers experienced 3.5 daily sessions. This suggests that rapid/ultra-rapid chargers are more utilised than AC chargers in terms of being used at least once a day on the ChargePlace Scotland public EV-charging network. The fact that rapid chargers tend to experience more average daily sessions also indicates that they are more well utilised; however, given the increased speed of charge that rapid/ultra-rapid chargers are capable of delivering, it is important to bear in mind that they are more likely to be able to facilitate more sessions per day than AC chargers.

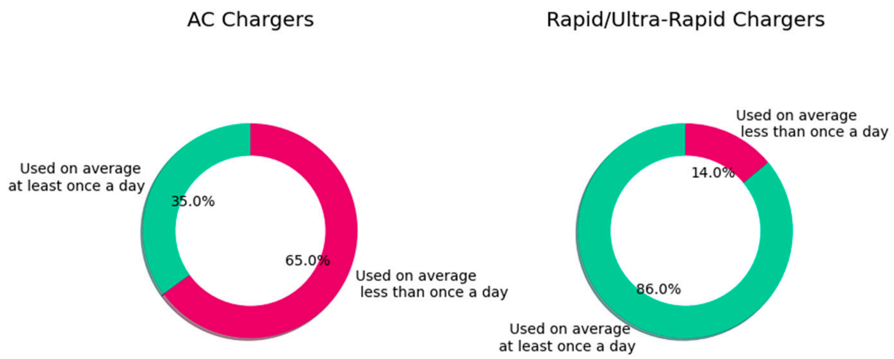

Figure 21. In total, 35% of AC chargers (**left donut chart**) experience at least one daily session, while 86% of rapid/ultra-rapid chargers (**right donut chart**) experience at least one daily session.

4.5.1. Top 5% Most Utilised AC Chargers

Ninety-two chargers make up the top 5% most utilised AC chargers by average daily sessions. These chargers experienced between 2.4 and 5.3 daily sessions on average. Figures 22–24 show that the most utilised AC chargers are mainly in urban, geographically accessible areas with low levels of deprivation.

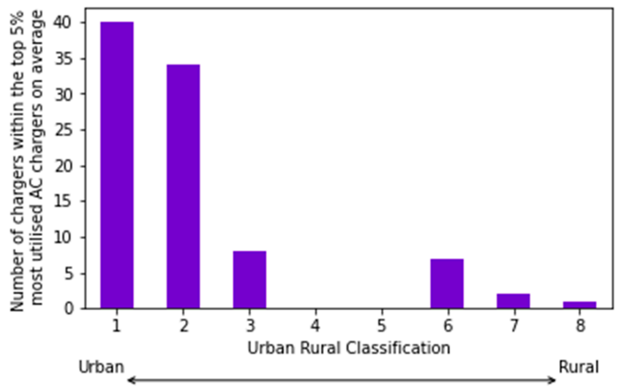

Figure 22. The number of chargers per Urban–Rural Classification that are within the top 5% most utilised AC chargers by average daily sessions.

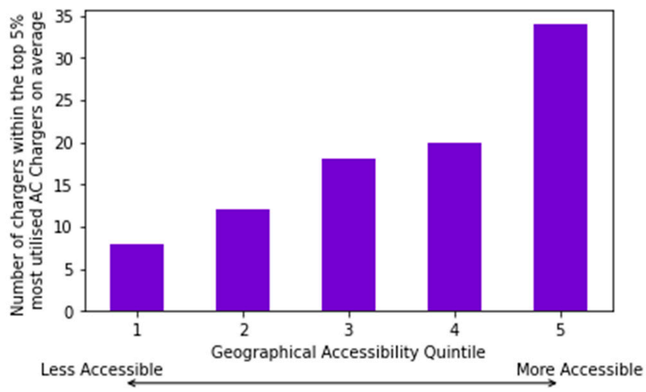

Figure 23. The number of chargers per Geographical Accessibility Index quintile that are within the top 5% most utilised AC chargers by average daily sessions.

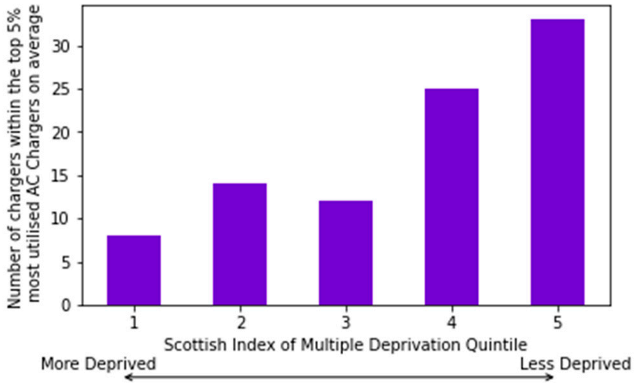

Figure 24. The number of chargers per Scottish Index of Multiple Deprivation quintile that are within the top 5% most utilised AC chargers by average daily sessions.

As demonstrated by Figure 22, only 10 of the most utilised AC chargers were classified as being located in rural areas (i.e., have an Urban–Rural Classification of at least 4). Furthermore, Figure 23 shows that the number of most utilised AC chargers increases as the Geographical Accessibility Index increases (i.e., there are more of these chargers located in more accessible areas). The least accessible quintile had 8 chargers, while the most accessible quintile had 34 chargers. Figure 24 illustrates that the least deprived Scottish Index of Multiple Deprivation quintile has the most highly utilised chargers (33 chargers in total), followed by the fourth (second least deprived) quintile, which had 25 chargers. The most deprived quintile had the lowest number of most utilised AC chargers, with eight chargers. As mentioned in Section 1, a chicken-versus-egg feedback effect can exist between the presence of public EV chargers and local EV adoption [9–11]. Therefore, it is possible that EV ownership is concentrated in these areas of high utilisation and that this is driving the above results. Additionally, as mentioned in Section 2.2.3, the least deprived areas tend to be more likely to complete journeys by car and have more awareness of EVs, which may mean that EV adoption is more likely to be focused here. These factors may also contribute to increased utilisation of local infrastructure.

4.5.2. Top 5% Most Utilised Rapid Chargers

Thirty chargers make up the top 5% most utilised rapid chargers by average daily sessions. Of the five ultra-rapid chargers included in the dataset, none were in the top 5% most utilised rapid/ultra-rapid chargers. The top 5% most utilised rapid chargers experienced between 8.4 and 12.9 daily sessions on average. Figures 25–27 show that the most utilised rapid chargers are mainly in urban, geographically accessible areas with high levels of deprivation.

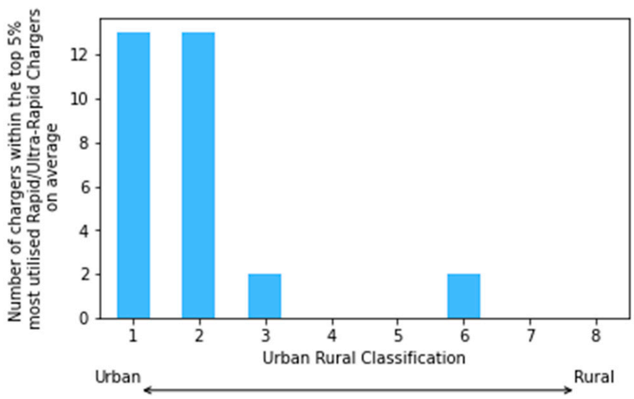

Figure 25. The number of chargers per Urban–Rural Classification that are within the top 5% most utilised rapid chargers by average daily sessions.

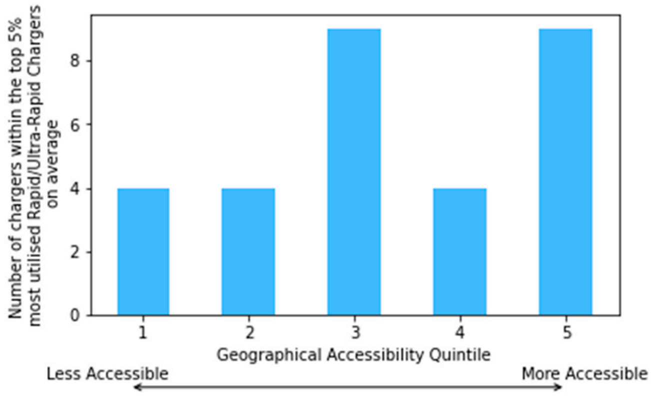

Figure 26. The number of chargers per Geographical Accessibility Index quintile that are within the top 5% most utilised rapid chargers by average daily sessions.

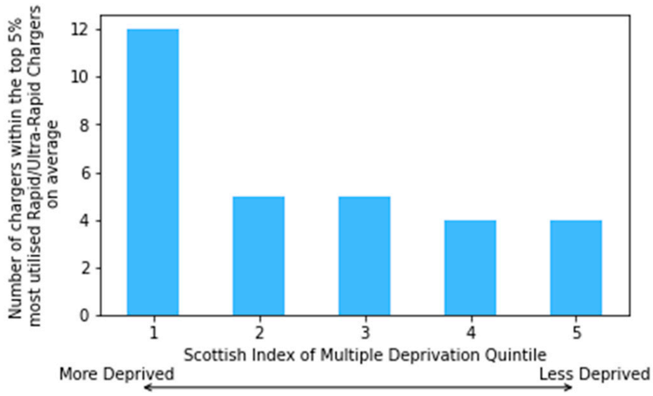

Figure 27. The number of chargers per Scottish Index of Multiple Deprivation quintile that are within the top 5% most utilised rapid chargers by average daily sessions.

As shown in Figure 25, only two of the most utilised rapid chargers were classified as being located in rural areas (i.e., have an Urban–Rural Classification of at least 4). Figure 26 shows that the most accessible quintile of the Geographical Accessibility Index and the third quintile (areas falling within the 60% least accessible in Scotland) had the greatest number of most utilised rapid chargers, with nine chargers. The first, second, and fourth quintiles all had four chargers each. Figure 27 shows that the most deprived quintile had the greatest number of most utilised chargers, with 12 chargers. The remaining quintiles all had similar numbers of chargers—the second and third quintiles both had five chargers, while the fourth and fifth quintiles both had four chargers. The significantly greater number of most utilised rapid chargers in the most deprived quintile is interesting; however, the Scottish Index of Multiple Deprivation is a relatively localised index, and there can be neighbouring areas of contrasting ranking [47]. Therefore, it is possible that people living in areas of higher Scottish Index of Multiple Deprivation value are using chargers located in areas of lower Scottish Index of Multiple Deprivation ranking.

4.5.3. Overview of the Most Utilised Chargers

Figure 28 shows three maps, one showing the position of all chargers included in the dataset, another showing the position of the top 5% most utilised AC chargers, and a third showing the position of the top 5% most utilised rapid chargers. It can be seen that the most utilised chargers tend to be concentrated in the central belt of Scotland, where the population is most dense and where the two main cities, Glasgow and Edinburgh, lie.

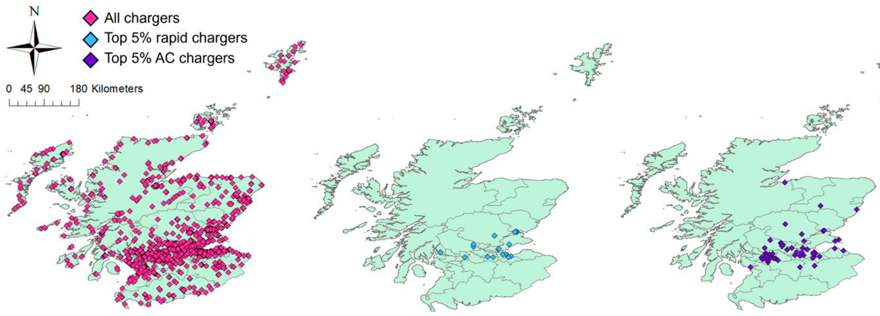

Figure 28. Positions of all chargers in the dataset (**left**), the top 5% most utilised rapid chargers by their average daily sessions (**middle**), and the top 5% most utilised AC chargers by their average daily sessions (**right**), including thematic layer representing local authority boundaries (reprinted from Ref. [39]).

In relation to research question 4 (concerning the characteristics associated with the most utilised chargers), our analysis of the developed dataset found that rapid/ultra-rapid chargers tend to experience more daily sessions on average and are more likely to be used at least once a day compared to AC chargers. The top 5% most utilised chargers of both speeds tend to be found in urban, geographically accessible areas. However, while the top 5% most used AC chargers tend to be located in less deprived areas, the top 5% most used rapid chargers tend to be located in more deprived areas.

4.6. Results Summary

Overall, the total number of charging sessions taking place on the ChargePlace Scotland public network slightly decreased between October 2022 and March 2024. Chargers were found generally to be more concentrated in urban areas; however, rural areas tended to have more chargers per head of population. Interestingly, areas falling within the 20% least deprived had the fewest chargers. Furthermore, areas falling within the 20% most accessible had the most chargers, with 794 chargers in total, but this was closely followed by areas falling within the 20% least accessible, with 621 chargers in total.

In general, weekdays tended to feature more charging sessions than weekends, peaking at an average of 101 sessions per 100,000 people on Fridays. Sunday had the fewest charging sessions taking place on average, with 84 sessions per 100,000 people. Charging times also tended to align with times of peak energy demand [68], with 84.4% of weekday sessions occurring between 8 a.m. and 9 p.m. However different areas, particularly the most rural, exhibited varying trends in charging session times (e.g., charging sessions in rural areas were more concentrated towards the middle of the day compared to urban areas). Exploring approaches to changing charging behaviours, the East Lothian trial of time-of-use tariffs saw a shift from 19.2% of sessions starting between 4 p.m. and 8 p.m. (the time period when the increased fee is active) to 15.7% of sessions starting between these hours. Introducing tariffs for chargers that were previously free to use induced an average reduction of 51.3% in the average number of daily sessions per 100,000 people and an average reduction of 50.0% in the average daily energy consumed per 100,000 people. However, the introduction of tariffs did not appear to have an effect on the utilisation of nearby chargers that remained free to use.

Generally, rapid chargers were found to be more well utilised than AC chargers. In terms of average daily sessions per charger, this ranged from 0.002 to 5.3 daily sessions for AC chargers and from 0.06 to 12.9 for rapid/ultra-rapid chargers. On average, AC chargers on the ChargePlace Scotland network experienced 0.9 daily sessions, and rapid/ultra-rapid chargers experienced 3.5 daily sessions. Furthermore, 35% of AC chargers on the network were used at least once daily, compared to 86% of rapid/ultra-rapid chargers. The top 5% most utilised chargers tended to be in urban, geographically accessible areas, while less deprived areas tended to have the most utilised AC chargers, and more deprived areas tended to have the most utilised rapid chargers.

5. Implications for Policy, Transport Planning, and Future Work

The results of this study provide insight into how a key public EV-charging network in Scotland is currently spatially distributed and used. A better understanding of these concepts can help to inform future development of the charging network, and, therefore, the results have important implications for policy, transport planning, and future research work. Specifically, there are implications for three key domains—power systems, charge point operators, and governance—and these implications are summarised in Figure 29. It is important to bear in mind the limitations of the research methodology, outlined in detail in Section 3.3. In particular, the limitations of locating chargers by their postcode, the difficulties that the Scottish Index of Multiple Deprivation has in capturing deprivation in rural areas, and the exclusion of chargers that were free to use from the analysis considering the most used chargers will have impacts on the results.

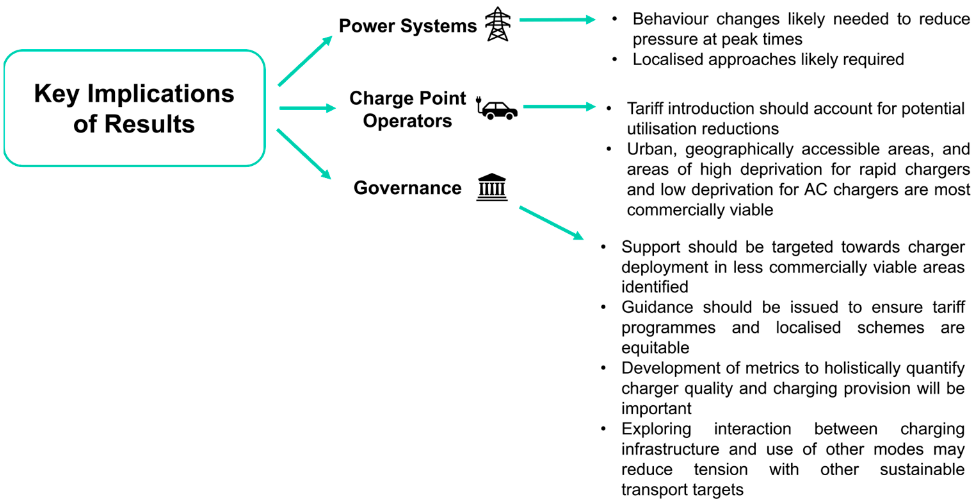

Figure 29. Summary of the key implications the results of this study have for policy and transport planning for three key stakeholders—power systems, charge point operators, and governance.

From a power systems perspective, encouraging and facilitating a behavioural change so that more charging sessions start at off-peak times during the week or on weekends could become important to relieve pressure on power network infrastructure. Time-of-use tariffs may be an effective tool to redirect utilisation away from peak hours. However, given that there are disparities between some location types (particularly the most rural areas) in terms of charger use-time patterns, charging behaviour changes may have different impacts in different areas. Therefore, a localised approach will likely be required, while careful attention should be paid to ensuring that differing approaches are equitable. For example, implementing differing charging fees at different times in different regions may unfairly disadvantage certain groups.

For charge point operators, if introducing a tariff programme for previously free-to-use chargers, it should be carefully planned and designed, accounting for potentially significant reductions in utilisation to allow a balance to be struck between market competitiveness and financial viability. Additionally, the slight decrease in the number of sessions across the ChargePlace Scotland network over the dataset time period may appear alarming for charge point operators. However, as discussed in Section 4.4, the reduction in utilisation as a result of the introduction of tariffs across different regions at different times could be a key contributor to this slight decrease. It is also possible that competition from other public EV-charging networks has caused a decrease in sessions taking place on the ChargePlace Scotland network. Furthermore, users who require use of the public EV-charging network due to a lack of residential or workplace charging alternatives may be more likely to reduce their car usage (e.g., use public transport or active travel for some journeys instead of driving) to offset increased charging costs after the introduction of a tariff—again, possibly contributing to the observed decrease over time.

Rapid/ultra-rapid infrastructure may be more commercially lucrative for charge point operators; however, the higher cost of this infrastructure compared to that for AC chargers [45,46] (see Section 2.2.2) should be carefully considered and factored into business decisions surrounding charger infrastructure speed. These financial factors, along with the needs of both charge point operators and users, are essential to determine the most appropriate charging infrastructure type to be installed. Additionally, the locations that tended to contain the most utilised chargers (i.e., urban, geographically accessible areas and areas of high Scottish Index of Multiple Deprivation for AC chargers and low Scottish Index of Multiple Deprivation for rapid chargers) are likely to be the most commercially viable location types for charge point operators to install chargers. Therefore, transport planning surrounding the deployment of additional chargers from a commercially focused viewpoint should prioritise these areas.

However, there may be tensions between commercial viability and ensuring that the transition to EVs is equitable, and it is important that other areas, particularly rural and less accessible areas, are not left behind. To enable an equitable transition, it will be crucial that there is sufficient public EV-charging infrastructure across all areas. The Scottish Government's public EV-charging rollout strategy via ChargePlace Scotland (see Section 2.2) may have contributed positively to the deployment of chargers in the more deprived and less accessible areas. By initially providing public funding for charging infrastructure, installation of public chargers in potentially less profitable areas has been encouraged. However, this approach may have led to discouragement of private sector involvement due to the substantial drops in charger utilisation after tariff introduction and the low utilisation rates of some chargers. Additionally, continued widespread funding from the public sector may be unsustainable, likely necessitating more targeted government support. Complicating infrastructure siting decisions is the ever-present chicken-versus-egg dichotomy (see Section 1) surrounding EV adoption [9–11]. If chargers are concentrated in areas of current high utilisation, it may discourage EV ownership in other areas due to a lack of infrastructure. Therefore, while private charge point operators may choose to focus development of infrastructure in the areas of high utilisation outlined above to maximise profitability, government intervention and supporting policy may be required to develop infrastructure in less commercially viable regions. This will be key to ensuring that there is equitable access to charging infrastructure, but also to ensuring that there is a wider equitable transition to EV adoption.

Additionally, although it is promising that the least accessible areas have a significant number of chargers, it is possible that these areas will require significantly more to service the populations found here across complex geographies. The metrics used to quantify current levels of charging infrastructure in different area types to inform development should be carefully considered. As evidenced by the disparity between trends found for the absolute number of chargers and the number of chargers per 100,000 people in each Urban–Rural Classification (see Section 4.2), varying metrics can represent the same situation differently. Therefore, defining a standardised set of metrics that holistically capture and quantify public charging provision in different regions will be an important step in developing an evidence-based foundation for public charging-network development. This could be particularly beneficial for guiding decision-making surrounding the siting of the additional 24,000 chargers by 2030, as pledged by the Scottish Government [3].

Charging sessions in rural areas being more concentrated towards the middle of the day may be because charging to complete a journey may occur more often in these areas, as rural residents tend to travel further than urban dwellers (see Section 4.2). However, the possibility that rural EV drivers may have to drive further to access chargers, also touched on in Section 4.2, may also be contributing to this trend. It is possible that charging infrastructure is located too far from users' homes for them to return there for the duration of the charge. Additionally, the location of chargers may feel unsafe or unpleasant at nighttime (e.g., if it is poorly lit or there is a lack of facilities, such as toilets, cafes, shops, etc.). Therefore, this may mean that charging during the day is preferable. Developing a metric to holistically quantify how safe and convenient chargers feel, accounting for entities such as proximity to other services and street lighting could help identify chargers whose immediate environment could benefit from improvement, which in turn may encourage more utilisation at times of lower demand.

Policy may also play a crucial role in ensuring that tariff programmes are equitable and encourage sustainable mobility practices. Although the introduction of tariffs did not seem to impact the utilisation of neighbouring free chargers, a different effect may be observed as EV ownership infiltrates consumers without residential charging, as mentioned in Section 4.4. Should the introduction of or changes to public charging tariffs influence behaviours through the incentivising of driving greater distances to access cheaper charging, this may threaten other government targets, such as the 20% reduction in car kilometres travelled [82]. To offset this, developing the charging network near public transportation hubs and incentivising charging here could promote the use of more sustainable modes for onward travel. However, there is a risk that this may rather encourage the undertaking of additional journeys rather than modal shifting of existing journeys, as has been seen in different price-related sustainable transport initiatives in other countries [83].

Outlining guidance on tariff design to help ensure that any possible disparities between regions (e.g., to encourage different behaviour changes in different areas, as touched on above) are equitable and do not disproportionately impact certain groups may become important. Additionally, such guidance could also consider how tariff programmes could support those without access to residential charging, which is typically cheaper than public charging. Circling back, in line with the chicken-versus-egg feedback effect, to penetrate this market and support the transition to EVs for these individuals, bolstering the public EV-charging network will be imperative. As mentioned in Section 2.2.3, given that 55.2% of trips are made by car in Scotland (with this rising to 69% specifically in the most rural areas) [51], fostering EV adoption equitably will play a crucial role in facilitating an overall reduction in emissions and the achievement of net zero in line with government targets.

Further work should aim to develop a suitable metric (or set of metrics) that will provide a holistic understanding of current charging provisions across different complex geographies. This may assist in the determination of the quantity of chargers that may be required to adequately provide for different regions, particularly the more rural and less accessible areas. Future work should also explore the kind of policy packages or appropriate governmental interventions that may effectively support public EV-charging infrastructure development in the less commercially lucrative regions identified herein. Additionally, regarding the time-of-use tariff programme analysis, this pilot scheme was relatively small in scale, and more research is warranted to understand the ability of such schemes to effectively facilitate behaviour changes and any other wider impacts in the Scottish context. This further work would ideally consider a similar tariff programme across a greater number of chargers over a wider area, ideally including different price thresholds for the 'peak time' fee. Future work is also warranted to investigate any impact public EV-charging tariffs may have on modal shifting (i.e., public transport or active travel use in place of car use) and to explore market competitiveness between different public charging networks in the Scottish context. Furthermore, there is value in undertaking an in-depth cost–benefit analysis of AC versus rapid/ultra-rapid chargers in Scotland, accounting for the utilisation of these chargers, the costs associated with their infrastructure, and the needs of both users and charger operators. Further work concerning the development of a means of measuring the quality of charge points, accounting for safety aspects and proximity to services, is also recommended to inform interventions which might encourage greater utilisation of underused chargers. Developing such a metric may require further data collection concerning the immediate environment of chargers. Collection of additional public charging data from the user's perspective, rather than the charger's perspective, may also prove beneficial, as this would facilitate a greater understanding of charging habits. For example, this may enable the identification of how many different chargers individual users tend to frequent, how far from their homes users prefer to charge, and how EV-charging interacts with the use of any other transport modes. These insights would contribute to a more informed and effective development of the public charging network.

6. Conclusions

This paper has developed and analysed a dataset of EV-charging sessions taking place on the ChargePlace Scotland network, spanning a total of 2786 chargers over the period from October 2022 to March 2024. The somewhat unconventional nature of the rollout of public charging infrastructure in Scotland, in tandem with the government's commitment to install an additional 24,000 public chargers by 2030, makes it pertinent to obtain insights into how the network can be developed effectively and equitably.

This paper has examined the current distribution of chargers, trends in charging times, the impact of tariff introduction, and the characteristics associated with the most utilised chargers. The limitations of this work include the possibility of slight inaccuracies in the length of time each charger was determined to be active, the geospatial assigning of some data due to limitations associated with locating chargers by postcode, and the limitations associated with the socioeconomic indicators considered (namely the Urban–Rural Classification and the Scottish Index of Multiple Deprivation). The results indicated that chargers currently tend to be concentrated in more urban areas, although the more rural regions had more chargers per head of population. In terms of deprivation, it was found that the 20% least deprived areas had the fewest chargers. Meanwhile, in terms of geographical accessibility, the 20% most accessible and 20% least accessible areas had the most chargers. Generally, weekdays experienced more sessions than weekends, and charging sessions on weekdays tended to follow a nine-to-five-style schedule, while sessions on weekends were more focused towards the middle of the day. However, there were disparities in patterns between different area types, with the most rural regions showing distinct usage patterns. Time-of-use tariffs showed potential for shifting charging away from peak times, though this analysis was relatively small-scale. The introduction of tariffs resulted in significant reductions in charger utilisation, with an average decrease of 51.3% in the average number of daily sessions per 100,000 people occurring after tariffs were introduced. However, this did not appear to shift demand to neighbouring free-to-use chargers. Rapid/ultra-rapid chargers tended to be more well utilised than AC chargers, with 86% being used at least once daily compared to 35% of AC chargers. While the most utilised chargers of both types tended to be located in urban, geographically accessible areas, the most utilised AC chargers tended to be in areas of low deprivation, and the most utilised rapid chargers tended to be in areas of high deprivation.

Based on these findings, the following insights pertaining to policy and practice were drawn: To relieve pressure on power network infrastructure, charging-behaviour changes may need to be shifted away from times of peak energy demand; however, regional disparities suggest that a localised approach may be required. Additionally, the Scottish Government should target support for charger deployment in the less commercially viable regions to facilitate EV adoption across all areas. The government could also provide guidance on equitable tariff design, particularly to ensure that any localised approaches are equitable, and policymakers should explore how charging provision could encourage or incentivise use of other sustainable modes. Furthermore, the development of holistic metrics to quantify charging provision and charger quality will be an important step in developing an equitable public EV-charging network. Further work should explore how these metrics surrounding charger quality and charging provision could be developed effectively and holistically, and such work could consider charger utilisation from a user's perspective rather than the charger's perspective. Such further work may require the collection of additional data. The findings of this study can provide useful insights to guide the development of the public EV-charging network in Scotland; make available a nationally representative dataset for further analyses; and supplement the existing research on public EV-charging networks across different international contexts that feature different infrastructure rollout strategies and network configurations.

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Appendix A

Figures A1 and A2 give the number of chargers per 100,000 people in each quintile of the Scottish Index of Multiple Deprivation and Geographical Accessibility Index, respectively.

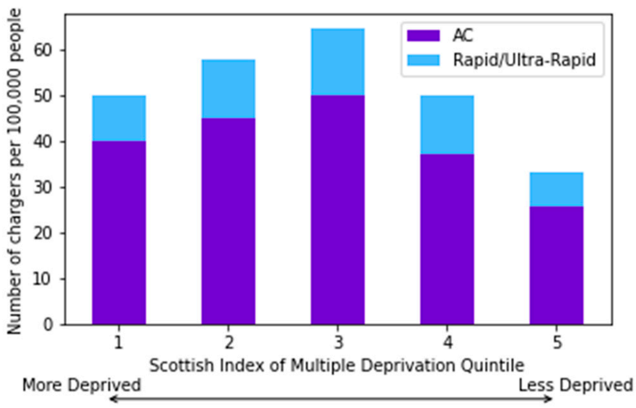

Figure A1. The number of EV chargers per 100,000 people on the ChargePlace Scotland public network found in each Scottish Index of Multiple Deprivation quintile, where a lower quintile generally indicates a more deprived area, and a higher quintile generally indicates a less deprived area.

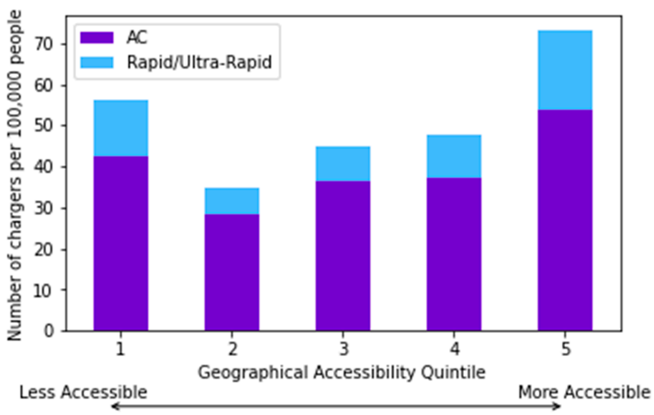

Figure A2. The number of EV chargers per 100,000 people on the ChargePlace Scotland public network found in each Geographical Accessibility Index quintile, where a lower quintile generally indicates a less accessible area, and a higher quintile generally indicates a more accessible area.

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