Charging Infrastructure and Policy Interventions to Support an Equitable Transition to Electric Vehicles in Scotland

Kathleen Davies

Department of Electronic and Electrical Engineering
University of Strathclyde, Glasgow

Thesis submitted for the degree of Doctor of Philosophy

April 2025

Signed: K Davies

Date: April 2025

Abstract

Electric vehicles (EVs) are thought to have the potential to contribute to more sustainable transport systems. However, the efficacy of the EV transition in Scotland to meet governmental emission reduction targets is unclear. Additionally, to support an equitable transition to EVs, it is pertinent to understand the current state and utilisation of public EV charging in Scotland, and the subsequent implications for development of an inclusive public charging network. Investigating the public charger population required by 2030 that will enable equitable geographic access to chargers will also be important.

Therefore, this thesis develops, validates and applies a system dynamics model of the Scottish road passenger transport sector to interrogate the efficacy of the following interventions up to 2030: modal shifting of sub-10km car journeys to active travel, modal shifting of medium-length car journeys to buses, achieving a majority electrification of the bus fleet, and replacing 50% of petrol/diesel cars with EVs. An extensive, nationally representative dataset of Scottish public EV charging sessions is then developed and analysed to gain insights into charger location and utilisation. Finally, the charger population required by 2030 under the modelling scenarios which achieved government targets is estimated.

Results indicate that the EV transition is predicted to be the most effective emission reducing intervention of those considered, although multiple interventions are likely needed to meet government targets. Analysis of the developed public charging dataset resulted in insights including quantified 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 charger population required by 2030 to ensure equitable access ranged between 7,546 and 46,606 chargers depending on the scenario, with charger technology being particularly impactful on the charger population required.

Acknowledgements

This thesis is dedicated to and in memory of my Granda - thank you for instilling in me the value of education, the importance of kindness and, on a much more personal note, the thrill of a bargain.

I would like to thank everyone who supported me throughout my PhD, I am very grateful to you all. In particular, I would like to thank Ed - I am beyond grateful for everything you have done for me, from introducing me to the world of research during my Game Changers internship to providing your invaluable guidance throughout my PhD. I feel very fortunate to have been able to work with you and have you as my mentor. To everyone at Arnold Clark, thank you for all our meetings, I thoroughly enjoyed each one and am grateful for your time and expertise. A special thank you to Audrey for being the strong female role model I needed throughout my PhD. To Obey, Anthony and Harry - thank you for keeping me going every step of the way from our first day of our undergraduate degrees all the way to our PhD journeys. Thank you to Stephen for your listening ear and supportive shoulder and to Kim for Big Cake expeditions. To Jonathan, thank you for being the best cheerleader, for all your good advice and for raising my spirits no matter what. To Connor, thank you for the kind soul that you are, for all your good energy and for always making me laugh. To Alex, thank you for the Norwegian hospitality, the Aussie (AUSSIE AUSSIE) family trips, and for always being there to brighten up any and every day no matter how close or far apart we are geographically. To Rich, thank you for all the tea, endless encouragement and for being on board with ordering too much takeout. To Mum, Dad and Peter - thank you, thank you, thank you for every single thing.

Contents

List of Figures

List of Tables

List of Acronyms

- a.m. - ante meridiem (before noon)
- BAU - Business as Usual
- CO_2 - Carbon dioxide
- EV - Electric Vehicle
- gCO_2/kWh - grams of Carbon Dioxide per kilowatt hour
- GDP - Gross Domestic Product
- GIS - Geographic Information System
- kgCO_2 - kilograms of Carbon Dioxide
- km - kilometres
- kWh - kilowatt hours
- MaaS - Mobility as a Service
- MtCO_2 - Megatonnes of Carbon Dioxide
- p.m. - post meridiem (after noon)
- UK - United Kingdom
- USA - United States of America

Chapter 1

Introduction

1.1 Climate Change and Scottish Government Response

The United Nations describes climate change as a 'global emergency' with devastating consequences for human health, infrastructure, development and delicate ecosystems [1, 2]. The World Meteorological Organisation confirmed that 2024 was the hottest year since records began at 1.55 degrees centigrade hotter compared to pre-industrial benchmarks [3]. This acts as a stark warning that immediate and careful action must be taken to reduce global emissions and mitigate impacts of climate change to benefit the international community.

The biggest emitting sector of greenhouse gases in Scotland is domestic transport [4], with road travel being a significant contributor to this and accounting for 66% of all transport-related emissions [5]. Therefore, transport poses a significant barrier to the achievement of net zero, the legally binding deadline for which is 2045 in Scotland [6]. Furthermore, the reduction of emissions is crucial to improving air quality, public health and fostering social equity among other positive externalities [7–9].

In response to the environmental challenges posed by travel, the Scottish Government set a transport-specific target to reduce emissions associated with transit by 56% by 2030, comparative to a 1990 baseline [10]. As a mechanism through which to achieve this, the Scottish Government also outlined a further target to achieve a 20% reduction

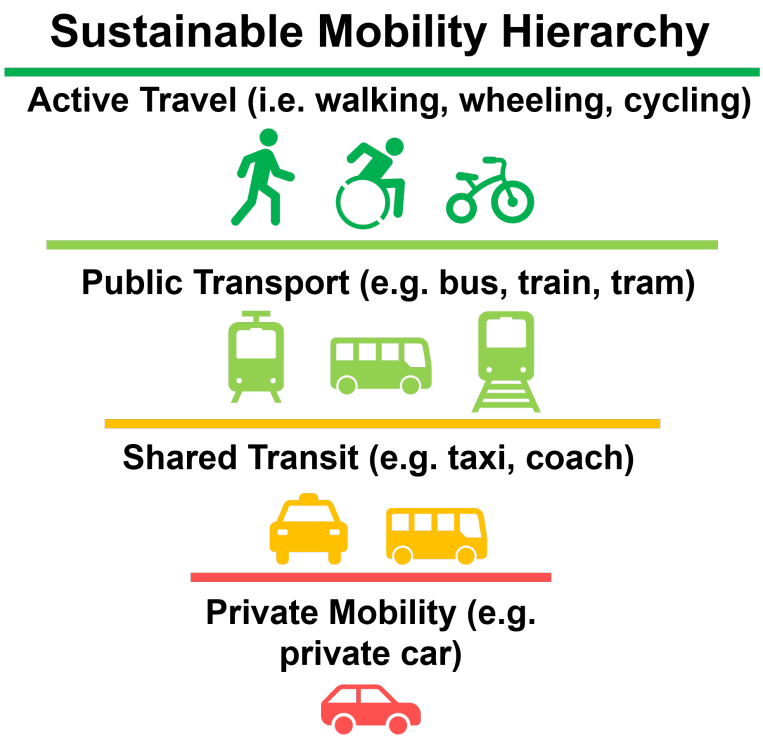

Figure 1.1: 'Sustainable Mobility Hierarchy', adapted from [16]

in car kilometres travelled by 2030 compared to 2019 levels [11] and a commitment to end the sale of new petrol and diesel cars by 2032 [12]. In January 2025, it was highlighted by Audit Scotland [13] that the 20% car kilometre reduction target was likely unachievable by 2030, primarily due to government inaction. Other government commissioned research [14] from December 2024, however, found that the target was potentially achievable via travel demand management strategies which featured road pricing, where drivers are charged to drive a car in certain regions or across certain distances. In March 2025, the Scottish Government announced their decision to place the target under review [15], meaning this target has a somewhat uncertain future and it is currently unclear if the target will be discarded, if the target deadline will be updated, or if the proportion of car kilometres to be reduced by 2030 will be changed.

Scottish Government published strategies, including the Car Kilometre Reduction Route Map [11], Roadmap to Widespread Electric Vehicle (EV) Adoption [17] and National

Transport Strategy [16, 18], provide an overview of interventions planned to achieve key transport emission reduction targets. Generally, visions of a modal shift away from private car usage and towards active travel (i.e. walking, wheeling if referring to wheelchair users, cycling, and the possible inclusion of electric micromobility modes such as electric bicycles or scooters [19, 20]) and public transport are set out in these policy documents. Figure 1.1 summarises this idea and shows the Sustainable Mobility Hierarchy which communicates that active travel modes should be most highly prioritised. Public transport closely follows active travel in the hierarchy, which in turn should be prioritised over shared transit, such as taxis or private coaches, and private mobility such as the private car.

Alongside a reduced car dependency, a transition away from petrol and diesel cars and towards EVs is also targeted by the Scottish Government. The transition to EVs poses significant potential for reducing the environmental impact of transport and effectively contributing to cleaner transport systems [21, 22]. However, the efficacy of the EV transition in the Scottish context, particularly in comparison with other planned sustainable transport interventions, is relatively unexplored.

Overall, the National Transport Strategy Delivery Plan [18] stipulates that shorter journeys should ideally be made by active travel; shorter to medium journeys should ideally be made via public transport; longer journeys should ideally be made by public transport and low-emission vehicles; and that most buses will be zero-emission by 2024. Meanwhile, the Roadmap to Widespread Adoption of EVs [17] sets out the aspiration that there should be a 50% reduction in the number of petrol and diesel cars by 2030, with many of these being replaced by EVs.

With governmental target deadlines rapidly approaching, and with the cumulative effect of emissions making prompt action imperative [23], it is pertinent that pathways to achieving these pressing targets are evaluated. It is vital to assess the likely impacts of the planned interventions on transport emissions in the Scottish context and to explore the relative importance of the EV transition with respect to other planned interventions.

Gaining an understanding of the efficacy of the interventions in terms of achieving key governmental targets will give important insights for policy and transport planning to enable critical transport emission reductions.

1.2 Electric Vehicles and their Charging Infrastructure

In this thesis, the term EV relates specifically to a passenger car powered by an electric rechargeable battery. As mentioned, the transition to EVs is generally highlighted as having the potential to reduce transport-related emissions and facilitate the achievement of a more sustainable transport network [21]. The realisation of a transition to EVs of the scale envisioned by the Scottish Government (as outlined in Section 1.1) requires that EV charging infrastructure be available and accessible.

Although home charging will play a significant role, with 84% of surveyed UK EV owners possessing a residential charger [24], the public EV charging network will have an undeniably important role. For instance, 90% of survey respondents reported regular use of public chargers [24]. 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 [25]. 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. Additionally, the Scottish Government set out their commitment and key aim of achieving an equitably accessible and inclusive public charging network in their vision for Scotland's public EV charging network [26].

Equity is a key concept in this thesis. In general, the term equity is closely related to the term equality – where all groups are treated equally and provided the same resources to meet an end. Equity on the other hand, considers the different needs and circumstances of different groups and adjusts the provision of resources to address imbalances and disparities in the different situations that different individuals may face.

Equity therefore entails that all groups are given fair, impartial treatment that is in line with their specific needs [27, 28]. In the context of this thesis, the term equity is specifically used in relation to an equitable EV transition and equitable provision of public EV charging. These concepts refer to ensuring that no groups are left behind as Scotland transitions away from petrol/diesel cars and towards EVs, that all groups are able to take part in this transition, and that all groups have sufficient access to EV charging according to their needs.

Moreover, there is evidence from other geographical contexts that public EV charging infrastructure tends to be disproportionately distributed in higher income, more advantaged areas [25, 29]. Specifically, a study of New York City [29] found that prevalence of public charging did not share a correlation with population density but did share a correlation with median household income, meaning that high income neighbourhoods were more likely to have access to charging infrastructure. Those on low incomes may also experience further barriers to the use of public EV charging including the financial cost of subscriptions to public charging networks; the financial cost of charging publicly which is generally more expensive than charging residentially; and limited access to smartphones which are often required to use public charging (e.g. via a mobile application) [25]. 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 [30–32], and there is evidence that charger installation and availability supports EV adoption [33, 34]. 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.

Additionally, an important consideration regarding public EV charging infrastructure is charger power rating. A higher charger power-rating commonly indicates a faster speed of charge and the power rating of chargers can generally be categorised into three charger speeds: AC (up to 22kW), Rapid (50kW) or Ultra-Rapid (150kW). 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 [35].

Charger power rating not only has implications for the speed of charge but can also have implications for battery health and the cost of the infrastructure. Frequent rapid charging has can cause more extensive battery degradation compared to use of slower charging speeds [36]. This effect may be more prominent for those charging in warmer climates [37]. There can also be disparities in the cost of charging equipment for chargers of different speeds, specifically it has been reported that AC chargers can cost up to £5,000 for one charging unit while rapid/ultra-rapid chargers can cost up to £26,000 for one charging unit [38]. Other costs will also be associated with charger installation, over and above the cost of the actual charger unit (e.g. for grid connection, signage, turfing, cabling, 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 £3,000, and this cost would be roughly equivalent to the connection cost for up to three AC chargers [39]. However, there is evidence that the costs relating to charger installation are decreasing [40, 41].

1.3 Public Electric Vehicles Charging in Scotland

The rollout strategy of public EV charging in Scotland took a relatively uncommon form. While many other countries opted for private sector driven rollout [42], the Scottish Government instigated their own public network called ChargePlace Scotland [43]. Government funding was awarded to public and private bodies to facilitate their ownership and operation of public EV chargers [44] on the ChargePlace Scotland network, with local authorities making up a significant proportion of charger owners [42]. Therefore, ChargePlace Scotland themselves do not own or operate the chargers but they do 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 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 [42]. The ChargePlace Scotland network remains dominant in the Scottish public charging landscape with just under 3,000 of Scotland's 6,000 public chargers being hosted on this network at the time of writing [43, 45]. The distribution of chargers across Scotland hosted on the ChargePlace Scotland network as of March 2024 is shown in Figure 1.2.

To support the transition to EVs in Scotland, the Scottish Government has pledged to supplement the existing 6,000 public chargers in Scotland by installing a further 24,000 public EV chargers by 2030 [46]. 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.

Additionally, it is pertinent to understand the likely charger population required in 2030 to support an equitable EV transition and enable an inclusive realisation of emission reduction targets. The Scottish Government's commitment to installing 24,000 chargers was adopted from a recommendation by the Climate Change Committee which was based upon 'relative car and van kilometres' travelled [49]. Alongside this, and as mentioned in Section 1.2, the Scottish Government have highlighted their commitment to develop a public network that is equitably accessible to all [26]. Using an approach based only on car kilometres travelled to quantify demand for public charging summarises car travel across the country into a singular value and assumes all activity takes place at one central point, meaning the distribution of people and places in not considered. Not accounting for the dispersion of the population likely means that some communities, particularly remote and rural ones, will be left behind. Therefore, it is vital to also explore the differences between methods that do and do not account for population dispersion to accurately understand the charger population required to enable an equitable transition of this scale.

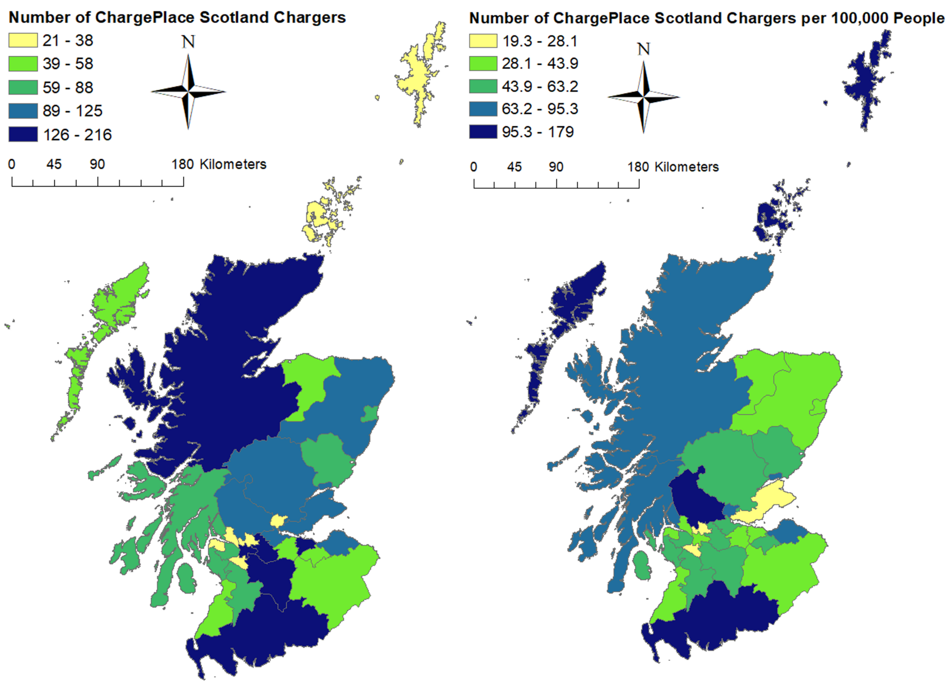

Figure 1.2: The number of chargers [43] (left) and number of chargers per 100,000 people [43, 47] (right) on the ChargePlace Scotland public EV charging network as of March 2024, including thematic layer representing local authority boundaries [48]

1.4 Research Questions

This thesis seeks to explore policy interventions and infrastructure required to support an equitable transition to more sustainable transport in Scotland. It aims to understand the efficacy of the transition to EVs in reducing emissions and achieving governmental targets in the Scottish context; the current state of public charging deployment in Scotland and the resulting implications for achieving an inclusive public charging network; and the EV charger population required by 2030 to have realised an equitable transition to EVs in Scotland. The latter aim is very broad, and so will be considered in the context of the spatial distribution of Scotland's population across high-density and low-density areas. Specifically, this thesis therefore seeks to answer the following research questions:

Research Question 1: How critical is the transition to EVs in Scotland, compared to other policy interventions, in the context of achieving the 2030 Scottish Government sustainable transport targets?

Research Question 2: What is the current state of Scotland's public EV charging network in terms of location and utilisation of chargers, and what are the related implications for realising an equitable transition to EVs?

Research Question 3: What scale of EV charger deployment is required by 2030 to ensure equitable geographic access to Scotland's public EV charging network?

1.5 Overview of Chapters

The remainder of this thesis is structured as follows:

Chapter 2 provides a background to the work and reviews relevant literature. The transition to EVs within the wider policy landscape is explored first, including an overview of previous works seeking to model impacts of similar sustainable transport interventions. Public EV charging behaviour trends are then explored, followed by an overview of public charging in Scotland and its socio-economic context. The focus then shifts to exploring literature relating to development of public charging infrastructure provision.

Chapter 3 aims to address Research Question 1 (*how critical is the transition to EVs in Scotland, compared to other policy interventions, in the context of achieving the 2030 Scottish Government sustainable transport targets?*) via the following sub-questions: a) What is the likelihood that the transition to EVs and other planned sustainable transport interventions will be sufficient to meet government mandated emission reduction targets? b) What is the likely efficacy of the transition to EVs compared with other planned interventions in reducing emissions in the Scottish context? To address these questions, this chapter develops, validates and applies a System Dynamics model of the Scottish road passenger transport system. Specifically, the impact of the following interventions on emissions and car kilometres travelled by 2030 is modelled: modal shifting of car journeys under 10km to active travel; modal shifting of car journeys between 10km and 40km to bus travel; the proportion of buses that are electric reaching 60% by 2024; and a 50% reduction in the number of petrol and diesel cars, with these cars being replaced by EVs. The results allow for an understanding of the contribution that the EV transition can make to the achievement of Scottish Government sustainable transport targets to be gained. Wider implications that the results have for policy and transport planning are also discussed.

Chapter 4 aims to address Research Question 2 (*what is the current state of Scotland's public EV charging network in terms of location and utilisation of chargers, and what are the related implications for realising an equitable transition to EVs?*) via the following sub-questions: a) Where are Scotland's public EV chargers currently located? b) When are Scotland's public EV chargers typically used? c) What evident impact does the introduction of tariffs have on Scottish public EV charger usage? d) What characteristics do the most utilised public EV chargers in Scotland have? To address these questions, this chapter develops and analyses an extensive, nationally representative dataset of public EV charging sessions taking place on a key network in Scotland. In addressing the sub-questions, implications for policy and practice regarding achieving a more equitable public charging network going forward are extrapolated.

Chapter 5 aims to address Research Question 3 (*what scale of EV charger deployment is required by 2030 to ensure equitable geographic access to Scotland's public EV charging network?*) via the following sub-questions: a) What is the impact of population distribution on the charger population required by 2030 in Scotland? b) How does charger technology impact the number of chargers required and what split of AC and rapid chargers will be required by 2030 in Scotland? To address these questions, this chapter aims to quantify the charger population required by 2030 in Scotland through both geospatially-agnostic (based on car kilometres travelled) and geospatially-driven (accounting for population dispersion) analyses. The results give insight into the charger populations required by 2030 in Scotland and provide an evaluation of the current Scottish Government targets for charging provision. Additionally, an understanding of the impact of the spatial dispersion of population on charging requirements is gained which

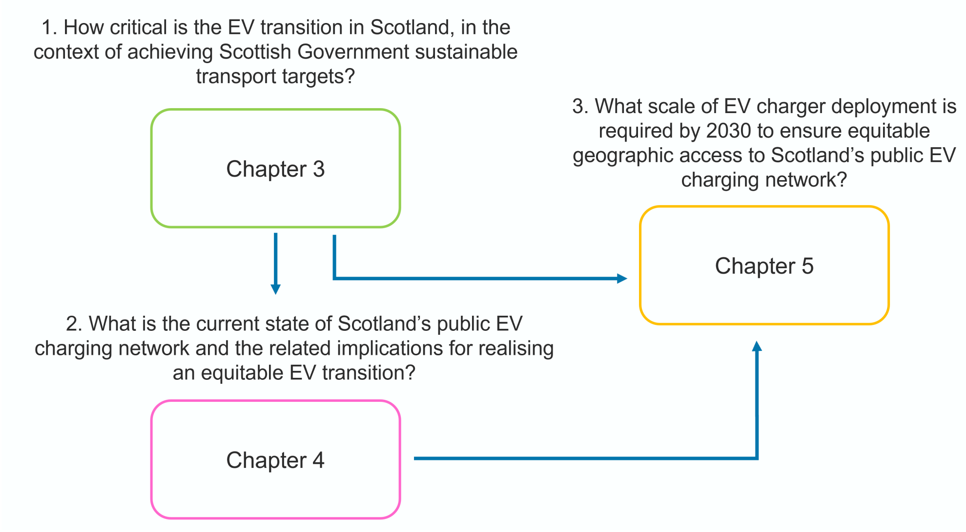

Figure 1.3: Overview of the thesis structure, highlighting the flow of the chapters and an abridged version of the research questions outlined in Section 1.4 with the relevant chapter that addresses them

will be an important consideration in facilitating equitable geographic access to chargers. As with previous chapters, wider implications of results for policy and practice are also explored.

Overall, key findings of this thesis include that the EV transition is likely the most critical intervention of those considered in Chapter 3 in terms of contributing to government emissions targets, although multiple interventions are predicted to be required to achieve targets. The government car kilometre reduction target was identified as a useful mechanism to reduce emissions although its achievement did not necessarily guarantee achievement of the government emission reduction target. Chapter 4 found that the introduction of charging tariffs resulted in a circa 50% reduction in the number of sessions taking place; that rural charging activity tended to be more concentrated towards the middle of the day compared to urban areas; that chargers tended to be less concentrated in the least deprived areas; and that while urban areas had a greater absolute number of chargers, rural areas had more chargers per head of population. Key findings from Chapter 5 include that the government target for the charger population by 2030 is likely sufficient to enable equitable geographic access to chargers with a rapid charging penetration of between 6% and 15%. The charger technology mix adopted and the effect of population dispersion were found to be impactful on the overall number of public chargers required to enable equitable geographic access. The total number of chargers required was also found to have a strong sensitivity to the acceptable service range of chargers. Figure 1.3 summarises this section and provides an overview of the thesis structure.

1.6 Publications and Research Outputs

All research publications and outputs concerning the work of this PhD thesis are outlined below.

Journal publications:

Davies K., Hart E., 2025. The required public electric vehicle charger population in Scotland under different future scenarios. Under review in npj (Nature Partner Journal) Sustainable Mobility and Transport.

Davies K., Hart E., Galloway S., 2024. Plugging-in Caledonia: Location and utilisation of public electric vehicle chargers in Scotland. World Electric Vehicle Journal 15(570). https://doi.org/10.3390/wevj15120570

Davies K., Hart E., Galloway S., 2024. Quantifying impacts of sustainable transport interventions in Scotland: A system dynamics approach. Transportation Research Part D: Transport and Environment 133(104311).https://doi.org/10.1016/j.trd.2024.104311

Published conference proceedings:

Davies K., Bayram I.S., Galloway S., 2022. Challenges and Opportunities for Electric Vehicle Retail Business. IEEE 3rd International Conference on Smart Grid and Renewable Energy (SGRE). Doha, Qatar, 20 – 22 March. https://doi.org/10.1109/SGRE53517.2022.9774055

Other published outputs:

Corbett H., Munoz C.C., Hannon M., Anderson P., Cairns I., Davies K., Galloway S., Hawker G., MacIver C., McGarry C., Turner K., Yarr R., 2023. Scottish Draft Energy Strategy and Just Transition Plan Consultation: University of Strathclyde Response. https://doi.org/10.17868/strath.00085444

Conference presentations:

'How GIS can enable widening access to electric vehicles', Energy Technology Partnership (ETP) Annual Conference, Online, 2021 (Oral Presentation)

'A Proposed System Dynamics Methodology for Quantifying the Impact of Sustainable Transport Policy on Energy Infrastructure and Society', Manchester Energy and Electrical Power Systems Symposium (MEEPS), Manchester, 2022 (Poster Presentation)

'A Proposed System Dynamics Methodology for Quantifying the Impact of Sustainable Transport Policy on Energy Infrastructure and Society', ETP Annual Conference, Edinburgh, 2022 (Oral Presentation)

'A System Dynamics Approach for Quantifying Wider Impacts of Sustainable Mobility Policy', All-Energy Exhibition and Conference, Glasgow, 2023 (Poster Presentation)

'A System Dynamics Approach to Quantifying the Impacts and Efficacy of Sustainable Transport Policy in Scotland', ETP Annual Conference, Glasgow, 2023 (Oral Presentation)

Awards and prizes:

Best Speaker Prize at the ETP Annual Conference 2023 Energy Policy, People and Society Session

Best Poster at the MEEPS 2022

Research for Industry Award at MEEPS 2022

Best Speaker Prize at the ETP Annual Conference 2022 Transport Session

Best Speaker Prize at the ETP Annual Conference 2021 Transport Session

Chapter 2

Background

2.1 Sustainable Mobility Interventions

As established in Chapter 1, the electrification of private cars is a key pillar to transport decarbonisation plans in Scotland, although this transition to EVs is hoped to happen alongside a shift away from car travel where possible. Decreased usage of the private car is thought not only to reduce transport emissions but also to achieve a more equitable transport network, as a move away from a car-centric system can be facilitated. A private car orientated transport system can disproportionately disadvantage those less likely to own a car such as women, the elderly, the disabled, those with lower incomes and some ethnic minority groups [9, 11, 50]. Prioritising a mode that some individuals cannot access may exacerbate inequalities and there is evidence that lack of access to the private car can contribute to social isolation and make access to key services such as healthcare problematic [51]. However alternative modes, namely public transport, also pose barriers to certain groups. Such barriers include cost and availability of services [52,53], which may disproportionately impact those on lower incomes and those living in rural areas respectively, and safety concerns [54], which may disproportionately impact women and girls. Furthermore, and as alluded to above, car ownership tends to be associated with having a higher income [9]. Therefore, those on lower incomes may are likely more reliant upon public transport to meet their transport needs. This reinforces that those with lower incomes are more likely to be disproportionately impacted by barriers to public transport.

Although car ownership is more prevalent amongst the more affluent, those on lower incomes still complete significant travel distances by car. Enforced car ownership, where owning a car is necessary to access key services and amenities due to a lack of other options (e.g. public transport), could further disproportionately disadvantage those on lower incomes as they must meet the costs associated with car ownership because they cannot access affordable alternatives [55]. These complex dynamics tie into the concept of transport poverty. Living in transport poverty is generally defined as experiencing a lack of access to, or affordability of, appropriate public or private transport modes needed to reach employment, education and fundamental goods and services [56, 57]. The concept of transport poverty is highlighted as one which can be challenging to effectively communicate because it is often related specifically to an individual rather than a household (unlike similar concepts such as fuel poverty which generally relates to the affordability of fuel for low income households). Specifically, it is possible that an individual in a household experiences transport poverty while the others in the household do not. This can occur, for example, when some members of the household belong to a protected group (e.g. an elderly member of a household situated in a region with few public transport options may not have the ability to drive a car and so experiences transport poverty, while the remaining members of the household are able to drive and thus do not experience transport poverty) [58].

Unequal distribution of transport resources (encompassing all key aspects of transport provision including car ownership, public transport services, active travel infrastructure and home delivery services) has been identified across the UK [57], highlighting that transport poverty exists and is an important issue. It has been identified that policy-makers have a weak understanding of the implications of transport emission reduction policy packages from an equity, transport poverty and social justice perspective. The lack of available data and standardised methods for quantifying impacts in this regard are key contributors to this issue [59]. Additionally, it is reported that experience of transport poverty has an impact on attitudes towards travel and travel behaviours.

Specifically, some individuals who have experienced transport poverty tended to alter their travel behaviours unexpectedly in response to affordability, unavailability or overcrowding of transport modes. As a result, the erratic nature of the travel patterns of those experiencing transport poverty may go undetected by national level transport surveys seeking to understand mode choice and travel time behaviours [60]. Such surveys are important to transport planning, meaning a vicious cycle can exist where development of transport provision for those who experience a lack thereof is being hindered by a lack of understanding of their experiences and needs. Additionally, a study [61] surveying the impact of the cost of living in Scotland on travel behaviour found that 26% of respondents altered their usual mode choice to make their travel more affordable. Those on lower incomes and ethnic minority groups were most likely to change their mode choice or avoid travel altogether in response to increasing living costs, with other groups including women, the disabled and rural residents also exhibiting similar behaviours. This highlights that sharp increases in the overall cost of living can exacerbate existing transport poverty.

To support a reduction in car dependence, the Scottish Government has supported multiple initiatives including zero-emission car clubs [62] and localised pilot schemes of Mobility as a Service (MaaS) [63], where generally a singular platform grants access to live travel information and the ability to plan, book and pay for travel services across multiple modes of transport. While some extant literature [64–68] explores the impact and effectiveness of planned policies in Scotland targeting reduced car reliance such as supports for MaaS and car clubs in other countries, these studies are often single policy focused, region specific and in many cases reliant on pilot projects as these initiatives are still in infancy.

Main findings from these works, which span geographical focuses of Ireland, the Netherlands, Germany and Sweden, include that car clubs pose the potential for increased use of more sustainable modes, reduced overall travel emissions and decreased car ownership [64] but crucially, a multifaceted approach combining fleet electrification and reduced car reliance gives the most effective emission reduction [65]. MaaS has been found by multiple studies to effectively promote a modal shift towards public transport and alternatives to the private car [66–68] by increasing the attractiveness, convenience and connectivity of these other modes. There is also evidence of the possibility that MaaS could drive a reduction in car ownership [68], however, this is contested by other literature [69, 70].

In Scotland, upon committing to reaching net zero by 2045, the national transport agency, Transport Scotland, commissioned a 2021 study [23] aiming to comprehend the policy outcomes necessary to achieve emission reduction targets in Scotland. This study considered broad scenarios including passenger and freight travel across road, rail, air and marine modes which featured 'rapid introduction' of low/zero-emission vehicles, modal shifting, and reduced overall travel demand. The scenarios modelled iteratively increased the number of features included (e.g. the first scenario featured the introduction of low/zero-emission vehicles, the next scenario featured both the introduction of low/zero-emission vehicles and modal shifting etc.), however, each feature was not simulated in isolation and so their individual impact was not explored. Additionally, the study does not provide detailed pathways to achievement of the scenario features. It was found that only the scenario including all the features (i.e. low/zero-emission vehicles, modal shifting and reduced travel) sufficiently met emission reduction targets, echoing other work [65] that highlighted the necessity for comprehensive approaches in tackling emissions. A key outcome of this work was the recommendation of instating a 20% reduction in car kilometres travelled target, which was consequently adopted by the Scottish Government.

A subsequent study [71] investigated the ability of planned policy packages (e.g. financial investments, legislative support for programmes) to reduce transport emissions. This found that legislation supporting a transition to EVs facilitated the most significant emission reduction, whilst policy packages broadly supporting a car kilometre reduction and bus fleet electrification also gave notable but less significant emission reductions. A specific breakdown of the impact of modal shifting policies was not provided.

Other work [72] highlights the importance of clean energy generation alongside transport electrification to harness the full potential this has to contribute to achievement of net zero. This study focused on Australia where only a small proportion of electricity generation is based on renewable sources. Specifically, it is reported that just 24% of electricity generation came from renewable sources in 2021 in Australia. It was found that net zero targets were only achievable where the transition to EVs was supported by a transition to 100% generation of electricity via renewable sources, highlighting the key supporting role that clean electricity generation plays in facilitating an effective EV transition.

The Scottish electricity supply is generated mainly from renewable and low carbon sources, with approximately 88% of electricity being generated from these sources in 2021. Wind, nuclear and hydropower were the most significant contributors to generation in this year, contributing circa 41%, 30% and 10% of the total generation respectively [73]. Additionally, the Scottish grid carbon intensity has been maintained below 50 gCO_2/kWh since 2017 according to the Scottish Government's Climate Change Monitoring Report 2023 [74]. This is a significant drop compared to previous years and there has been an overall decline in the Scottish grid carbon intensity since 2010, when there was a carbon intensity of 320 gCO_2/kWh [74]. Based on the average energy consumption of an EV [75], this translates to charging emissions of 0.062 gCO_2/km in 2010 versus 0.0098 gCO_2/km in 2019 (assuming vehicle energy consumption remains constant), making EVs over six times less polluting in 2019 due to this reduction in grid carbon intensity. In comparison to petrol/diesel cars however, which have carbon emissions factors of 0.17 gCO_2/km [76], EVs in 2010 would still have been significantly less polluting.

2.2 Modelling Transport Systems Techniques

Various different techniques and mathematical modelling approaches have been used in previous literature to model the EV transition and wider transport system problems including Bayesian networks, fuzzy cognitive mapping, causal mapping, choice modelling, agent-based modelling and system dynamics [77, 78]. Some modelling techniques are termed bottom-up approaches which are based upon the behaviours of individuals [79]. These approaches have been applied in several transport-related previous works, being used for example to model transport emissions on a street level [80] and to provide improved estimates of transport emissions in Ireland [81]; to investigate demand for transport services and energy, and resultant emissions in China and the USA [82]; and to explore the impact that reduced demand for transport can have on transport emissions and public health in the UK [83]. A key strength of bottom-up modelling is its ability to capture relevant aspects on a detailed sectoral level [80, 84]. Meanwhile, top-down approaches (which are generally based on aggregated data and operate on a high-level basis [79, 80]) have been identified as more flexible and transparent than bottom-up approaches, and better equipped to investigate national level transport analyses, particularly in the context of the UK where there are many stakeholders involved in transport provision including local governments and private operators [85].

Agent-based modelling can be considered an example of a bottom-up modelling approach [79]. Agent-based modelling techniques can facilitate identification of trends and behaviours across a given study population through the modelling of autonomous agents that represent individual people or certain groups. These agents are capable of decision-making based upon their assigned attributes and relationships they share with other agents and their environment [86]. This modelling tecnhique has been applied to different problem contexts, for example considering the impacts of MaaS scheme attributes on mode choice [66], the effect of access to residential charging on EV penetration [87], and the impact of supplying up-to-date traffic information on driving behaviour [88]. However, weaknesses of agent-based approaches are that: model validation can be a challenging process [89, 90], especially when the model is simulating less well-documented relationships; a broad range of assumptions must be made at the discretion of the modeller with limited standardised guidance on these processes which can significantly impact results; obtaining a balance between comprehensibility of the overall model and accuracy of agent behaviour can be challenging; and agent-based models tend to be highly specific to the aims for which they were developed to address, limiting their relevance to other related problem contexts [90].

Another bottom-up method of modelling transport systems is choice modelling [79] which can capture how individuals make decisions. In previous work, the use of choice modelling in the transport domain has allowed for insights into: the influential factors in EV drivers' decision to use public chargers [91, 92]; the impact of public charging availability on EV adoption [93]; and route choice behaviours to inform traffic volumes [94]. Choice modelling can give valuable insights into how people make trade-offs between different entities [95]. However, key challenges and limitations of these methods include availability of data; the assumption that humans take a maximising approach to decision-making (choosing the best possible option) rather than a satisficing approach (choosing an option that satisfies minimum requirements) which is contested [96]; and the fact that human behaviour is challenging to accurately capture (for example, in stated choice surveys, the choice that respondents report they will make may not translate directly to the choice they may make in real life) [92].

Other modelling techniques feature a more visual underpinning structure which can enable more effective communication of methods, concepts and results to key stakeholders. Bayesian networks are one such technique which have been used for various applications including to model transport demand and behaviour [97, 98]. Bayesian networks are also known as probabilistic causal models [99]. They take the visual format of connected nodes which are referred to as parent and child nodes and involve a quantitative approach featuring a robust inference method based on Bayes' theorem (a mathematical expression for determining conditional probability [100]). They can effectively manage uncertainty which makes them attractive for application to real-world problems. It is possible to create a Bayesian network structure through expert knowledge, machine learning using data or a combination of both, with the latter being the recommended option [97]. However, they are acyclic in nature and so cannot handle feedback loops to accommodate temporal aspects to the modelling. Additionally, where expert knowledge elicitation is concerned, probability concepts can be hard to grasp and think in terms of for some experts [101], making this method less comprehensible for experts to contribute to when creating the model and also less accessible for those unfamiliar with the concepts to interpret the model's results. This could be a particular issue when applied to transport policy and infrastructure problems, as policymakers and other key stakeholders with diverse backgrounds and expertise who the results are relevant to, may struggle to fully grasp the implications of results.

Causal mapping approaches involve the visual representation of cause-and-effect relationships between variables. They are qualitative and allow for comprehensive and time-effective [102] expert knowledge elicitation. They can contain dynamic relationships and support feedback loops, however they cannot effectively represent uncertainty. Additionally, inferring direct results using them is challenging, not least because there is no standardised technique for doing so. Eliciting the expert knowledge to create the map also has no standardised approach [101], with various techniques including structured (where experts are given a predetermined list of variables and asked to define the relationship between them) and unstructured (where experts are initially asked a broad series of questions, followed up with more specific ones to reach conclusions on relationships between variables) interviews being employed [103]. Being based on expert knowledge also introduces a degree of subjectivity to this approach and causal maps give a 'static' description [101,102] of variables and their causal relationships as they do not communicate how expert beliefs can change when presented with new information surrounding variables in the map.

Similar to causal mapping is fuzzy cognitive mapping. Again, such techniques involve visual mapping of causal relationships between variables, although fuzzy cognitive mapping involves a specific value being assigned to indicate the strength of the relationship between variables. Although this method is conducive to effectively eliciting expert opinion and can easily facilitate the breaking down of a larger complex problem into smaller pieces, the subjectivity of expert opinion in the absence of available data [78] and the lack of a standardised approach for defining the relationship extents can make this method problematic. Specifically, different scales for scoring relationship strengths are utilised in different works, including scales of 0 to 1, 30 to 31, 0 to 100, 32, -1 to 1 and 33 to 34 [104].

Overall, considering transport systems and future scenarios requires a powerful method. System dynamics modelling is a top-down approach [79] making it potentially more attractive than bottom-up analyses for conducting transparent, national-level transport analyses [85] as mentioned above. Its underlying concepts can be effectively communicated accessibly [78] and it relies on visual diagrams, making the modelling mechanisms and results intuitive to explain to wide audiences. System dynamics has also been identified in previous work as particularly suitable for policy-related scenario analysis [105, 106]. Its ability to effectively manage feedback loops [107] allows for projections of changes in variables over a set time period to be gained, making it a more suitable choice for time-based analysis compared to a method like Bayesian networks. It also supports the use of diverse sources, knowledgebases and datasets [78]. Due to these strengths making system dynamics modelling an effective approach to scenario-based future projections, it will be used to undertake the analysis outlined in Chapter 3 of this thesis. System dynamics techniques will be discussed further in Section 2.2.1 below.

2.2.1 Evaluating transport system future scenarios using System Dynamics modelling

System dynamics modelling captures cause and effect relationships between variables within the system and can provide a holistic analysis by combining diverse variables (e.g. technical, environmental, social and/or economic). This, in turn, allows for scenario-based analyses which facilitate the interrogation of realistic policy landscapes. A 'stock and flow' diagram acts as the foundation of system dynamics modelling. There are several different variables included in these diagrams, as demonstrated by Figure 2.1, which gives an example of a 'stock and flow' structure that could feature in a more expansive 'stock and flow' diagram. Specifically, stocks (i.e. the variables in boxes) represent accumulations; flows (i.e. double-lined black arrows) represent rates;

and limits (i.e. cloud-like structures) signify that what is fed into or out of these points are outwith the system's boundaries [107]. Variables that may be outside system boundaries are deemed of low/negligible relevance to the problem considered. Stock variables are assigned an initial value. The value of stock variables are then influenced by flows [108] and are the integral of flows passing into the stock variable minus flows passing out of the stock variable plus the initial value [107]. While stocks are indicative of the system's state, flows are indicative of activity within the system [108]. All other variables in the model are auxiliary variables and the blue single-line arrows connecting them to other model features indicate causal relationships. Deterministic equations describe the relationships between linked variables. However, it is important to bear in mind that system dynamics techniques do carry limitations, particularly their inability to handle uncertainty or account for spatial aspects of a problem [109], and their assumption that the system's circumstances and causal relationships between variables do not change over time [110].

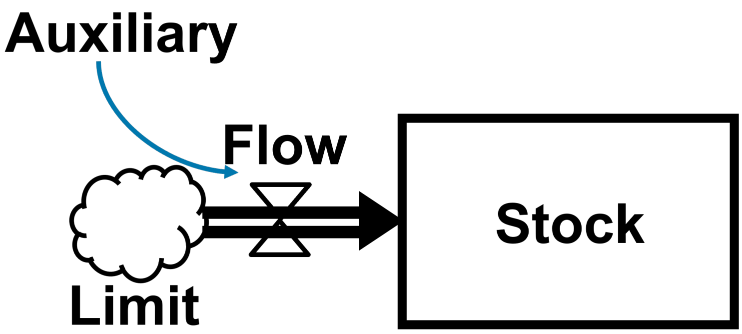

Figure 2.1: Example of variables and structure that may feature in a system dynamics stock and flow diagram

Previous work [111] studied the transport network in rural China, using system dynamics techniques to understand the impact of sustainable transport policy, namely the provision of subsidies for low emission vehicles and the electrification of the bus fleet. The developed system dynamics model concisely encapsulates the makeup of the transport system and how it operates and emits CO_2, and included core variables capturing population, economy, modes of transit, road infrastructure, distance travelled by each mode, CO_2 emissions and legislation. Scenario-based analysis was applied, forecasting the impact of varying degrees of low-emission vehicle subsidy provision and electric bus penetration on CO_2 emissions, bus usage and proportion of internal combustion engine vehicles. The model used in this work can be categorised as a small or mini model, meaning it has a minimum number of variables and feedback loops needed to accurately capture the most critical insights. Such small models allow for a balance to be struck between computational efficiency, modelling accuracy and model comprehensibility [112].

Various other works have used system dynamics to consider the impact of initiatives targeting reduced travel emissions in various locations and with varying policy designs. For example, studies have investigated the wider impacts of MaaS provision [113], modal shifting of long-distance car journeys to rail [114], modal shifting for freight transportation [115] and public transport electrification [116] in the geographical framework of Sweden, Germany, Brazil and China respectively. The ability of system dynamics to handle diverse variable sets and intricate relationships makes it singularly attractive for the analysis of complex transport network and policy problems. Furthermore, system dynamics can effectively manage feedback loops and accommodate scenario-based analysis, allowing for system variables' responses to policy intervention and trends over time to be captured [107] and making this method applicable to this problem context.

2.3 Public Electric Vehicle 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 thesis (i.e. Scotland [42, 117, 118] or the UK [119]), while others focus on different geographical contexts including the USA [120–122], Germany [32, 123], the Netherlands [124, 125] and Ireland [126]. Additionally, some other studies use public EV charging data from Scotland and apply this to technical models to give insight into charging network utilisation [127–129] and network development [130], and a study of charging behaviour in Norway uses data from a stated preference survey [91].

Regarding research focused on public EV charging in Scotland, [117] 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. 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 [118] considered also the months of August 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 was 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 1 charger for every 2 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 1,071 licensed EVs [118] in Scotland by the end of 2014, compared to 38,512 by the end of 2022 [76]) and there were very few chargers on the network so little data available (i.e. August 2013 had 619 recorded sessions and August 2014 had 2,885 recorded sessions [117] while August 2015 had 12,939 recorded sessions and August 2016 had 26,119 [118]).

Looking to 2022, the ratio of ChargePlace Scotland chargers to licensed EVs in Scotland has regressed to approximately 1 charger to 16 EVs [76, 131] (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, although this target was updated to a goal of providing 1kW of power via public chargers per EV as the ratio of chargers to EVs differs between countries [132]. 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 [133]. 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 3,105 EVs per 100,000 people. The Netherlands with its low ratio of chargers to EVs has 2,637 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 [134]. Additionally, the ratio of chargers to EVs may disguise strategic decisions to invest more significantly in faster chargers [133, 135]. For example, although the Netherlands has a more favourable public charger to EV ratio, the average power of chargers in the Netherlands is 19kW compared to 81kW in Norway [134].

Other previous work [42] introduced a method informing 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 future. Interestingly, this study found that the likelihood 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, [119] considers 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 focused 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 22kW, 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, [127] applies a Monte Carlo simulation to a small dataset of public EV charging sessions in Perth and Kinross covering a single day time 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. Other work [130] proposes 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. The case study allows for an evaluation of infrastructure development strategies to be made. Additionally, [129] proposes 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, [128] proposes 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 was used.

Concerning work from different geographical focuses, [121] considers public EV charging session data from the USA exploring chargers of lower (i.e. between 3kW and 19.2kW) and higher (i.e. between 50kW and 350kW) power-ratings at different location types (e.g. offices, shops, 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. This work also highlights the need for a better understanding of free and low-cost pricing structures for public EV charging.

Additionally, [126] explores 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, 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, although petrol stations tended to have shorter charging sessions compared to the other locations. This work also discusses 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 [32, 121, 123, 126], that faster chargers tend to be preferred and experience higher utilisation [91, 119, 121, 126] and that different types of areas will generally have unique charging infrastructure requirements [125, 126]. 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 [91]. Additionally, some studies [32, 120, 124, 125] 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 [124] 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, socio-economic factors and types of urban and rural communities) but particularly due to the somewhat unconventional rollout strategy of public charging in Scotland. Additionally, some works focus on time periods early on in the context of EV adoption [126] and analyse relatively small datasets [120, 126]. 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.

2.4 ChargePlace Scotland Public Electric Vehicle Charging Network

As discussed in Chapter 1, ChargePlace Scotland is a key public EV charging network in Scotland, and the work outlined in Chapter 4 of this thesis will develop and analyse an extensive dataset of charging sessions taking place on this network. As was also mentioned in Section 1.3, although the overall charging network is government owned, the individual chargers on the network are owned and operated by various organisations in both the public and private sectors, with local authorities owning a significant proportion of chargers.

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 [44] 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 in Renfrewshire remained free to use at time of writing [43]). 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. As mentioned in Section 1.3, approximately half of all Scotland's public chargers are hosted on the ChargePlace Scotland network, meaning that there is currently a circa 50/50 split of public versus private investment in Scotland's charging infrastructure. 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 [44].

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 thesis, 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 [137,138]. 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

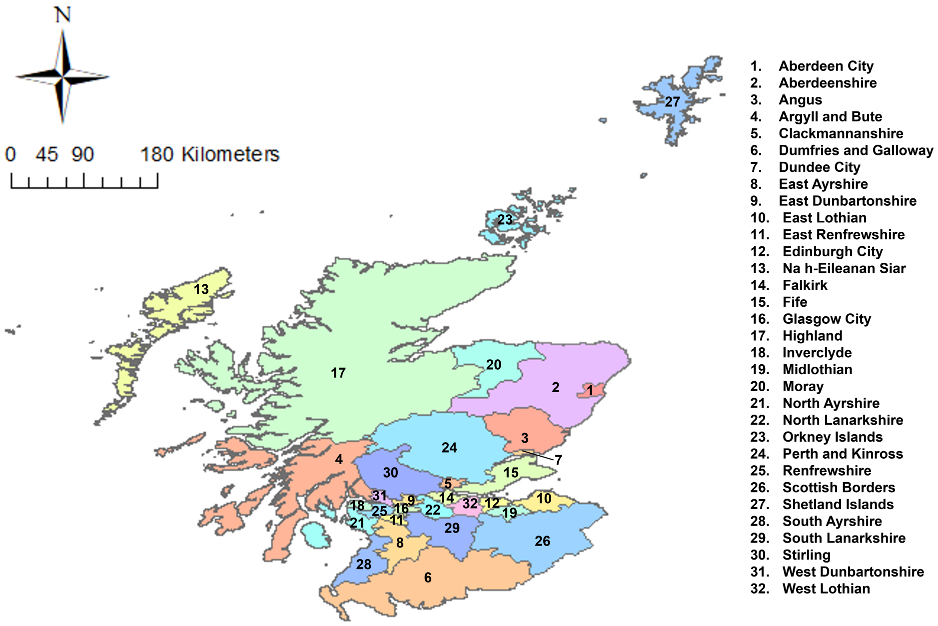

Figure 2.2: Map of Scotland's local authority areas (adapted from [136]), including thematic layer representing local authority boundaries [48]

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 [139]. For context, Figure 2.2 provides an overview of the local authorities in Scotland.

However, the ChargePlace Scotland network has an uncertain future. As of Spring 2025, no more funding will be provided to any local authorities or public and private organisations to own and operate chargers on the ChargePlace Scotland network [140]. Although the Scottish government will continue to support public charging deployment through an Electric Vehicle Infrastructure Fund, the decision to end further ChargePlace Scotland funding marks a significant shift in infrastructure development strategy in Scotland.

2.5 Scottish Public Charging Socioeconomic Context

For spatial distribution of public chargers in Scotland to be equitable, it will be 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 [141] and the Urban Rural Classification [142].

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 [141]. The index gives each area a value between 1 and 6,976, with 1 being the most deprived and 6,967 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 [143].

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, shops) and access to digital services (i.e. broadband connection) [143]. 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 [144]. 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 3,000 to 9,999 people and less than 3,000 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 drive from such a community [142]. The Urban Rural Classification, in combination with the Scottish Index of Multiple Deprivation and its Geographical Accessibility 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 [145] 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 is 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 [145], 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, 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. Specifically, awareness of EVs as a mechanism to achieve more sustainable transport ranged from 74% of respondents in the most deprived regions compared to 90% of respondents in the least deprived regions. Therefore, there are clear interactions between these key socioeconomic indicators and transport in Scotland.

2.6 Developing Public Electric Vehicle Charging Provision

As described in Chapter 1, the Scottish Government has adopted the Climate Change Committee's car and van kilometre based recommendation to install an additional 24,000 public chargers by 2030 [49, 146]. A car kilometres based approach for understanding future public charging requirements has also been used by previous work considering the United Kingdom [147]. This report from the International Council on Clean Transportation considered two scenarios for EV adoption by 2030, one where

50% of new car sales are EVs and one where 70% of new car sales are EVs, and assumed that 80% of drivers have access to private charging options. Key findings of this study include that Scotland is projected to require a total of 8,948 public chargers by 2030 when 50% of new car sales are EVs and a total of 11,180 chargers when 70% of new car sales are EVs.

Additionally, [148] uses car distance travelled in their method to quantify charging demand on both a city and national level in Denmark, also considering car ownership and residential and workplace parking circumstances. The public charging demand in a scenario where all cars are EVs is determined using data from the Danish national transport survey. Comparing the findings for Denmark overall and only its capital city of Copenhagen reveals that although Copenhageners travel shorter car distances than the national average, they have a larger public charging demand due to the much lower availability of private residential parking. This highlights the importance of accounting for access to residential charging options when considering public charging needs. According to the Scottish House Condition Survey [149], 44% of households in Scotland do not have access to private, off-street residential parking, indicating this will be a significant element of public charging requirement quantification in the Scottish context.

However, as also mentioned in Chapter 1, a car kilometres based approach for quantifying charging demand assumes all activity occurs in one place and the dispersion of population is not accounted for, meaning some communities will likely be left behind. Approaches that account for the spatial distribution of people, places and other aspects often use geographic information systems (GIS) software. Previous works undertake analyses using GIS to understand public charging requirements across various international contexts including the USA [150], Thailand [151], India [152], United Arab Emirates [153], Canada [154], the UK [155] and Ireland [156].

A previous study [150] uses GIS to understand if siting rapid public EV chargers at existing petrol stations could adequately meet demands for public charging in five cities in the USA – Los Angeles, Denver, Raleigh, Salt Lake City and Santa Clara. A maximum covering location problem approach is taken, where the aim is to locate the minimum number of chargers such that the maximum amount of demand for charging is met. The charging demand is represented by a set of demand points which in this case are the centroids of census data zones and these are weighted by population and traffic data. A demand point is defined as being serviced if a charger is located within a certain distance of it, with this study modelling two simulations of this distance as 5km and 10km. The coverage of demand points achieved by existing rapid chargers was compared with the projected coverage achieved if rapid chargers were sited at existing petrol stations. It was found that across all five cities considered, locating rapid chargers at petrol stations achieved a higher coverage of demand compared to the existing rapid chargers. However, key limitations of this approach include that demand can only be represented by the centroid of a data zone and census data zones such as that used in this study have varying land areas. Additionally, the method cannot accommodate partial coverage of a demand point (and therefore of a census data zone) by a charger.

Another study [151] uses a similar maximum covering location problem approach and considers Thailand on a national level. A square 5km x 5km grid is applied across the land area of Thailand and the grid cells are used as the data zones in this work. This study provides a comprehensive overview of optimal locations for chargers across the entire country and calculates the number of chargers required across the nation by dividing it into six sub-areas. However, this study bases demand for public infrastructure in a certain sub-area on current EV adoption rates within that specific sub-area, assuming that these will remain constant going forward. This leads to results which generally project a higher number of recommended chargers in areas of higher EV penetration compared to areas of lower EV penetration. Although it is important to ensure there is adequate charging provision in areas of high EV adoption, as mentioned in Section 1.2, not positioning sufficient chargers in areas of lower adoption can hinder the transition to EVs in these areas as part of the chicken-egg feedback effect.

Other work [152] aims to site slower EV chargers in the city of New Delhi, India, particularly accounting for traffic flows. This study also divides the area of interest into a square grid where in the modelling framework chargers would theoretically be situated at the centroid of a grid cell and therefore the dimensions of the grid act as the service range of chargers. Grid square dimensions of 3km x 3km were chosen in line with local governmental targets that set out that chargers should not be more than 3km apart. It is assumed that 60% of drivers charge residentially with the remaining 40% relying on the public network, and projections for EV penetration in 2030 and origin-destination data which gives information on traffic flows are used to project the demand for public charging in each grid cell. However, hexagonal grids are generally identified as a more appropriate shape compared to square grids for these kind of applications [153, 157]. Hexagons are more similar in shape to circles than squares are, and points along edges and vertices are closer to the centroid. The distance between the centroid of a hexagon and the centroid of all six of its neighbours is also the same in a hexagonal grid, which is not the case for a square grid. This is important in these kinds of studies involving grid partitioning of a study area as generally chargers are taken to be sited at the centroid of data zones and the data zone dimensions act as the service radius of the chargers. Additionally, hexagons tend to have a better fit to curves compared to squares, meaning that generally they can provide a better fit to land borders.

Other previous works [153–156] combine the use of GIS and multi-criteria decision analysis techniques to identify specific optimal charger locations in cities. Using multi-criteria decision analysis to explore suitability or extent of charging requirement of potential sites for chargers can give a holistic understanding of these issues by incorporating diverse important factors. However, such analyses often involve the use of expert surveys, interviews and/or similar techniques which can be subjective. Some of these studies [155,156] include residential on-street chargers within their scope that, although they may be considered as being sited publicly, aim to act as home charging facilities for those without access to a driveway or other private off-street parking. Provision of such chargers, whether made available publicly or semi-privately, will be important to an equitable transition to EVs.

2.7 Background Summary

In summary, previous literature [64–68] explores some of the impacts of sustainable transport policies that are planned in Scotland. However, these works are often focused on solitary initiatives and are localised, considering different territories and regions, which may possess different complex geographies, varying cultural attitudes and mind-sets (regarding transport), and different climates and socio-economic characteristics compared to Scotland. While previous work has considered future transport emission reduction scenarios in Scotland including modal shifting and the transition to EVs [23], the efficacy of individual interventions is not explored meaning a comprehensive comparison between interventions cannot be made and specified pathways to achievement of the modelled scenario features are not provided. Other work [111,113–116] considering the impact of interventions on transport systems uses system dynamics techniques which have been shown to be an effective method for this application, especially for simulation of scenarios. Chapter 3 will therefore develop, validate and apply a system dynamics model of the Scottish road passenger transport system to provide a deeper understanding of the efficacy of the planned transition to EVs and other sustainable interventions to reduce emissions and car kilometres in line with Scottish Government targets.

Previous literature also explores and discusses public EV charger utilisation, considering charging session data from various international contexts. These works provide valuable insight into how public EV chargers are used to inform development of public charging infrastructure. However, these studies often use relatively small datasets [117, 119, 120, 126], consider data from relatively early on in the transition to EVs [117, 119, 126], and/or are specific to different geographic focuses [32, 120–126], meaning their relevance to Scotland can be limited due to differing public charging rollout strategies or geophysical and socio-economic factors. Additionally, the need for further exploration of free and low-cost pricing structures for public EV charging was highlighted by previous literature [121]. This indicates a need to conduct analysis of charging data specific to the Scottish context to better understand utilisation trends and to make specific recommendations for the expansion of the network here, accounting for its unique socioeconomic landscape, and its relatively uncommon charging tariff structure. Chapter 4 therefore will develop and analyse an extensive, nationally representative dataset of public EV charging sessions taking place on the ChargePlace Scotland network enriched by additional external socioeconomic indicators. In doing so, insights into the unusual rollout strategy of public charging driven by public funding and provision of free charging are gained and aspects of public charging in the Scottish context are definitively quantified, consolidating the broader understanding of public charging utilisation in the international context.

In terms of projecting the charger population required, previous works have used different methods including those that have taken a car kilometres travelled based approach [147, 148], similar to the report that informed the Scottish Government's commitment to install a further 24,000 public chargers by 2030 [49, 146], and others that take a more geospatially based approach [150–156] capturing dispersion of people, places and other aspects. Some works incorporate techniques such as multi-criteria decision analyses [153–156] and maximum covering location problem approaches [150, 151] to their geospatial analyses to identify charging needs. However, multi-criteria decision techniques can introduce a level of subjectivity due to the inclusion of expert opinion and maximum covering location problem approaches generally cannot accommodate partial coverage of demand by chargers. Meanwhile, other works take a grid partitioning approach [151–153], dividing the area of interest into a grid of repeating geometric shapes with hexagonal grids having been identified as a particularly effective grid pattern [153, 157]. This approach takes the dimension of each grid cell as the service radius of chargers. Again, the previous studies conducted give valuable insight into future public charger populations required and regions likely to face the highest demand, however, these studies are country or city specific limiting their applicability to the Scottish context. Furthermore, the use of the different approaches (i.e. car kilometre based and geospatial analyses) warrants exploration of the impact of the distribution of people and places on the charger population required by 2030 in Scotland. Chapter 5 will therefore estimate the number of public chargers required in Scotland by 2030 using two different methods - one based on car kilometres travelled in line with previous work informing Scottish Government infrastructure targets [49], and another incorporating hexagonal grid partitioning in GIS to account for population dispersion and therefore to estimate the charger population that can enable equitable geographic access to chargers. In doing so, future Scottish charging requirements and the gap-risk of a non-spatial charger population estimation are quantified.

Chapter 3

Quantifying the Impact of the Electric Vehicle Transition on Transport Emissions

3.1 Introduction

As discussed in Section 1.1, to mitigate the negative impacts of travel on the environment, the Scottish Government has set a target to reduce emissions associated with transport by 56% by 2030, comparative to a 1990 baseline [10], and a further target to achieve a 20% reduction in car kilometres travelled by 2030, compared to 2019 levels [11]. As has been outlined, Scottish Government policy [17, 18] sets out a vision to achieve these targets where shorter journeys are made by active travel; shorter to medium journeys are made via public transport; longer journeys are made by public transport and low-emission vehicles; most buses will be zero-emission by 2024; and that there will be a 50% reduction in the number of petrol and diesel cars by 2030, with many of these being replaced by EVs. However, with deadlines for reaching targeted emission reductions quickly approaching, understanding the efficacy of planned interventions is pertinent.

This chapter addresses the need to rigorously quantify the likely ability of planned interventions to reduce car kilometres travelled and, in turn, the emissions resultant from transport. In particular, the relative efficacy of the EV transition to reduce transport emissions with respect to other planned interventions in the Scottish context will be explored. With other international governments acknowledging the significant obstacle that transport poses to their own emission reduction plans and adopting similar strategies to Scotland (e.g. the Irish Government has also outlined a similar target to reduce car distance travelled by 20% by 2030 in their Climate Action Plan for Transport [158]), the case for thoroughly investigating such interventions is further strengthened. This chapter therefore aims to evaluate the implications of scenarios relevant to the Scottish Government vision for a sustainable transport network.

Specifically, this will focus on the modal shifting of car journeys under 10km to active travel by 2030; the modal shifting of car journeys between 10km and 40km to bus travel by 2030; the proportion of buses that are electric reaches 60% by 2024; and a 50% reduction in the number of petrol and diesel cars by 2030, with these cars being replaced by EVs, in line with government aspirations [16, 17]. The presented analysis utilises system dynamics modelling, motivated by its successful application to other research problems in the transport sphere as discussed in Section 2.2 [111, 113–116]. System dynamics is a powerful, time-based modelling technique that can effectively manage feedback loops and non-linear relationships, aspects which are essential for the exploration of policy impacts and possible future scenarios associated with the Scottish road passenger transport sector.

In summary, the presented analysis models the impact of the following interventions, based upon Scottish Government ambitions, on the road passenger transport system in Scotland:

- Modal shifting of car journeys under 10km to active travel
- Modal shifting of car journeys between 10km and 40km to bus
- Proportion of buses that are electric reaches 60% by 2024

- The total car stock in 2030 will contain no more than 50% of the number of petrol/diesel cars in 2022, with these cars being replaced by EVs

In doing so, this chapter seeks to address Research Question 1 as outlined in Chapter 1 - *How critical is the transition to EVs in Scotland, compared to other policy interventions, in the context of achieving the 2030 Scottish Government sustainable transport targets?* Additionally, the following sub-questions are explored:

a) What is the likelihood that the transition to EVs and other planned sustainable transport interventions will be sufficient to meet government mandated emission reduction targets?

b) What is the likely efficacy of the transition to EVs compared with other planned interventions in reducing emissions in the Scottish context?

The remainder of this chapter is structured as follows: Section 3.2 details the methods used, namely system dynamics modelling and scenario-based analysis; Section 3.3 details the results and provides a discussion of the findings; Section 3.4 explores the implications that these results have for policy, transport planning and future work, and Section 3.5 gives a conclusion.

3.2 Methodology

To interrogate the efficacy and likely ability of planned interventions to reduce transport emissions in Scotland, a system dynamics model was developed using Simantics System Dynamics Version 1.35.0 open-source software [159]. As discussed, system dynamics techniques were utilised for their suitability when conducting scenario-based and policy related analyses in the transport sphere [111, 113–116].

The high-level structure of the developed system dynamics model was informed by previous work [111]. The model captures socioeconomic variables; the composition of the road passenger transport fleet; the vehicle kilometres travelled by the relevant modes and their emissions, and is used to make forecasts of trends of these variables under different scenarios. The following subsections detail the overall research methodology, including model development, validation and scenario specification.

3.2.1 Model Development

The model developed in this chapter was heavily adapted from that in [111] in order to be applicable to Scotland's road passenger transport system. The structure of the stock and flow diagram in [111] was considered as a high-level starting point, and Scotland equivalent data on variables within the system was collected. The collected data was interrogated through application of regression techniques to understand the nature of relationships present between variables in the Scottish context. Some subsequent structural adaptations were made to the stock and flow structure in [111], informed by the nature of the relationships explored via regression analysis of Scottish data, to ensure the model was appropriate for to application the Scottish context. For example, the inclusion of buses in the model was significantly adapted due to the relatively stable nature of bus activity in Scotland, described in more detail below. 'Under the hood' of the model, deterministic equations describing interactions between variables were derived, also via regression analyses of Scottish transport and socioeconomic data, which will be outlined in more detail in Section 3.2.2. Although some logical equations (e.g. the total distance travelled is equal to the sum of the distance travelled by each mode) from [111] were retained (as indicated in Table 3.1), the equations developed to project Scottish passenger transport trends were generally the result of the application of a numerical procedure to Scottish data and equations were fitted to provide a low error (further described in Section 3.2.2).

Figure 3.1 illustrates the model 'stock and flow' structure which underpins the modelling framework, showing all model variables and outlining the modules contained, namely a socioeconomic module, vehicle fleet and infrastructure module, vehicle kilometre module and emissions module. These modules feed into each other in this order from left to right. Details of the model configuration are provided below, followed by details of the derivation of the deterministic equations that define the relationships between linked variables in the system.

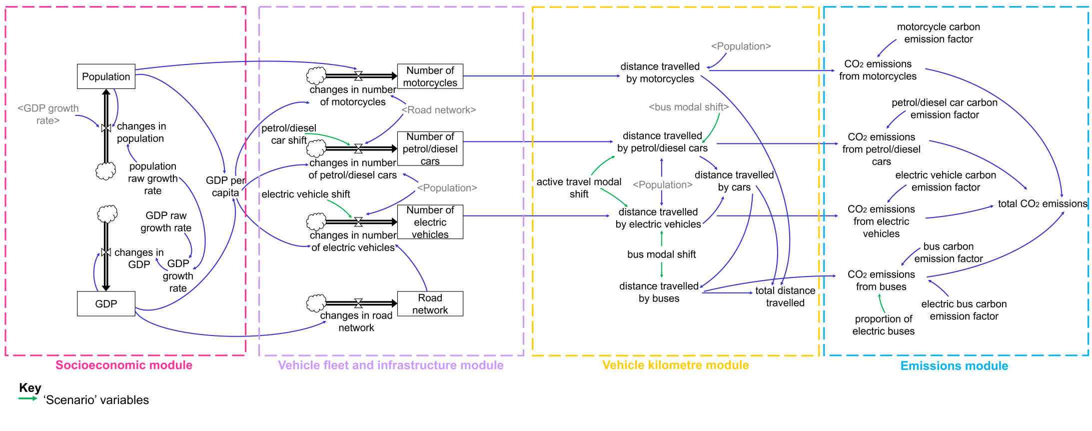

Figure 3.1: Stock and flow diagram developed and validated to capture the Scottish road passenger transport system, high level structure adapted from [111]

Socioeconomic Module: The socioeconomic module captures population and gross domestic product (GDP), which are key variables used to drive the modelling. It should be noted that GDP accounts for Scottish onshore GDP only. The socioeconomic module feeds into the vehicle fleet and infrastructure module and informs the forecasting of variables contained there.

Vehicle Fleet and Infrastructure Module: The vehicle fleet and infrastructure module projects the share of each vehicle type, namely motorcycles, EVs, and petrol/ diesel cars, in the road passenger transport system. Vans, hybrid cars, range extended EVs, and diesel and electric motorcycles were not included. The values for each vehicle type were based on the number of licensed vehicles in Scotland. It should be noted that it is possible that there may be vehicles licensed here that are operated elsewhere (e.g. in other nations in the UK) and vice versa. There are two scenario variables in this module, 'petrol/diesel car shift' and 'electric vehicle shift'. These variables ultimately influence the number of petrol/diesel cars and the number of electric vehicles, in line with the applied scenarios detailed in Section 3.2.3. The composition of the vehicle fleet is used to predict the distance travelled by each vehicle type.

It is noteworthy that although buses are not featured in this module, they are included in the model, however, due to the relatively stable nature of bus vehicle kilometres travelled in Scotland (i.e. the bus distance travelled has steadily decreased from 346 to 336 million vehicle kilometres between 2010 and 2019 [160]), this variable is treated as a constant. In this time frame (i.e. 2010 to 2019), bus passenger journeys also decreased from 430 to 363 million journeys [160]. Multiple factors are thought to contribute to the decrease in bus passenger journeys in Scotland including changes in bus fares and service provision; increased competition from the private car due to increases in ownership rates; and increased competition from online options for shopping and working [161]. As bus service provision (i.e. bus distance travelled) decreased by approximately 2.9%, the bus usage (i.e. number of passenger journeys) saw a greater decrease of circa 15.6%. Therefore, it was assumed that there is spare capacity on existing buses and the variable was assigned the average value of bus vehicle kilometres travelled across the time period 2010 to 2019 [5]. The bus mode is therefore represented in the vehicle kilometres module instead.

Vehicle Kilometre Module: The vehicle kilometre module uses the composition of the vehicle fleet to forecast the vehicle kilometres travelled by each vehicle type. It is assumed that the proportion of each car fuel type translates directly to the proportion of all car kilometres travelled that the fuel type is responsible for (i.e. if 90% of all cars are petrol/diesel cars, then petrol/diesel cars are responsible for 90% of all car kilometres travelled). There are two scenario variables in this module, 'active travel modal shift' and 'bus modal shift'. These variables influence the distance travelled by cars and buses respectively. The distance travelled by cars (petrol/diesel and EVs) is a key output of this module.

Emissions Module: The emissions module uses the predicted vehicle kilometres of each vehicle type to forecast the resultant emissions of each category using vehicle-specific carbon emission factors. The carbon emission factors [162] used in all simulations for petrol/diesel cars and motorcycles were the values provided for 2023, therefore it was assumed that vehicle efficiency was constant throughout the simulation period.

Average vehicle size (according to the UK Government greenhouse gas reporting conventions [162]) was also assumed. Additionally, for 'petrol/diesel cars', the carbon emission factor for petrol was used as this was the slightly larger of the two by a very small margin. Carbon emission factors of electric buses and EVs were included to capture emissions associated with charging, and were calculated [163] by multiplying the average efficiency of the vehicle (car [75]; bus [164]) by the maximum Scottish grid carbon intensity between 2017 and 2020 according to the Scotland Climate Change Monitoring Report, 2023 [74]. It should be noted that the efficiency of electric buses was informed by a study [164] featuring a relatively small sample size, short time frame and a geographical location different from that of this work. There is one scenario variable in this module, 'proportion of electric buses'. This variable influences the CO_2 emissions of buses. The total CO_2 emissions of the Scottish road passenger transport system is a key output in this module.

3.2.2 Modelling Deterministic Relationships

The deterministic equations that describe the relationship between linked variables in the model were formulated through regression modelling using MATLAB [165] and Scottish socioeconomic and transport data. Different forms of regression (e.g. linear, polynomial, exponential) were trialled to find the most appropriate expression for each variable. In trialling these different forms of regression for each variable, the model was calibrated to give a mean absolute percentage error of less than 10% during model validation which is discussed further in Section 3.2.4. The regression type that gave the lowest mean absolute percentage error for each variable was selected. Multiple linear regression was used for all variables with the exception of 'change in number of EVs', which used exponential regression. Table 3.1 details the equations, resulting from this regression analysis, utilised in the system dynamics model. Regression data sources are also provided. Note that not all deterministic equations were the result of regression analysis. Equations in the socioeconomic and emissions modules (according to Figure 3) and the 'total distance travelled' equation were informed by previous literature [111] and logical reasoning (e.g. the equation for the total emissions from all modes is the sum of the emissions from each individual mode).

Table 3.1: Deterministic equations used in the model. Numerical parameters within the equations are the result of the outlined regression analysis using Scottish transport and socioeconomic data, the sources of which have been provided

Variable (units)	**Deterministic Equation**	**Source**
Changes in population (people)	Population × (population raw growth rate + 0.02 × GDP growth rate)	[111]
GDP growth rate (dimensionless)	raw GDP growth rate + 0.01 × population raw growth rate	[111]
Changes in GDP (£million)	GDP × GDP growth rate	[111]
GDP per capita (£)	(GDP × 1000000)/Population	[111]
Changes in number of motorcycles (vehicles)	(-0.01966597396) × Population + 2.244465309 × GDP per capita + 0.314697936 × Road network + 21847.70266	[76, 166–168]

Continued on next page...

Variable (units)	Deterministic Equation	Source
Changes in number of petrol/diesel cars (vehicles)	Population × (-0.2197432104) + GDP per capita× 21.86963814 - Road network × 4.741946148 + 830053.8732 + petrol/diesel car shift	[76, 166–168]
Changes in number of electric vehicles (vehicles)	EXP(-97.493) × EXP(Population × (-4.6103E-07)) × EXP(GDP per capita × 0.00039271) × EXP(Road network × 0.0016843) + electric vehicle shift	[76, 166–168]
Changes in road network (km)	0.001637× GDP - 139.271	[5, 167]
Distance travelled by motorcycles (km)	IFTHENELSE(Number of motorcycles>=0, Population × (-70.1756) + Number of motorcycles × 2749.243 + 4.7E+08, 0)	[5, 76, 168]

Continued on next page...

Variable (units)	Deterministic Equation	Source
Distance travelled by petrol/diesel cars (km)	IFTHENELSE(Number of petrol/diesel cars>=0, (Number of petrol/diesel cars × 11390.44997 + Population × 2453.347274 + (-5566156817)) × (1 - (active travel modal shift + bus modal shift)), 0)	[5, 76, 168]
Distance travelled by electric vehicles (km)	IFTHENELSE(Number of electric vehicles>=0,(14444.19276 × Number of electric vehicles + 2.748522506 × Population + (-14560376.24)) × (1 - (active travel modal shift + bus modal shift)), 0)	[5, 76, 168]
CO_2 emissions from motorcycles (kgCO_2)	carbon emission factor motorcycle × distance travelled by motorcycles	[111, 162]
CO_2 emissions from petrol/diesel cars (kgCO_2)	carbon emission factor petrol/diesel car × distance travelled by petrol/diesel cars	[111, 162]

Continued on next page...

Variable (units)	**Deterministic Equation**	**Source**
CO_2 emissions from electric vehicles (kgCO_2)	distance travelled by electric vehicles × carbon emission factor EVs	[74, 75, 111]
CO_2 emissions from buses (kgCO_2)	(carbon emission factor bus × distance travelled by buses × (1-proportion of electric buses)) + (proportion of electric buses × carbon emission factor electric bus × distance travelled by buses)	[111]
Total CO_2 emissions (kgCO_2)	CO_2 emissions from petrol/diesel cars + CO_2 emissions from motorcycles + CO_2 emissions from electric vehicles + CO_2 emissions from buses	[111]
Total distance travelled (km)	distance travelled by buses + distance travelled by electric vehicles + distance travelled by petrol/diesel cars + distance travelled by motorcycles	[111]

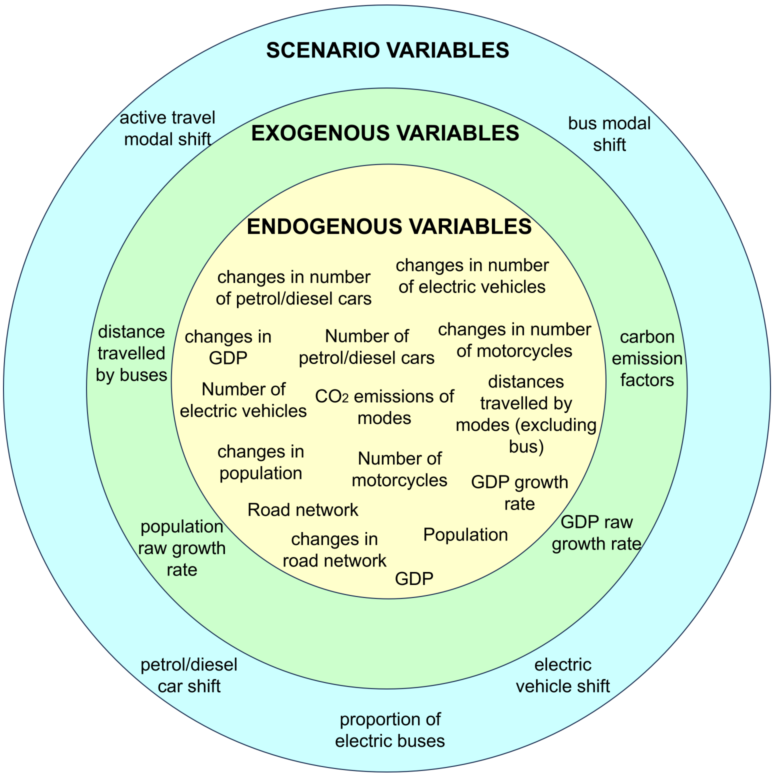

Figure 3.2: Bullseye diagram separating the model variables into categories of scenario, exogenous and endogenous variables

Figure 3.2 shows the categorisation (i.e. exogeneous, endogenous, and scenario variables) of the variables contained within the developed system dynamics model. The scenario variables control the application of the scenario-based analysis, further described in Section 3.2.3. The exogenous variables are externally determined and have the ability to impact the system but are not themselves impacted by the rest of the system. In contrast, the endogenous variables are determined within and impacted by the system [108]. Table 3.2 provides the initial conditions for stock variables for both the validation and scenario analyses, and Table 3.3 provides the exogenous variables' inputs for both the validation and scenario analyses. Where applicable, data was generally taken for the fourth quarter of each given year. Note that in Table 3.3, for the 'distance travelled by buses', the value excluded from the parenthesis is the average bus vehicle kilometres travelled for the period 2010 to 2019 [5], while the expression in parenthesis which adds the modal shifted vehicle kilometres is divided by the average bus capacity in Scotland [169] to approximate the resultant bus vehicle kilometres to be added. Carbon emission factors in Table 3.3 refer to well to wheel emissions.

Table 3.2: Stock variable initial values for both validation and scenario simulations

Variable (units)	**Validation Simulation Initial Condition (2010 Value)**	**BAU/Scenarios Simulations Initial Condition (2022 Value)**	**Source**
Population (people)	5,262,200	5,436,600	[168, 170]
Scottish GDP (£million)	145,051	187,300	[167, 171]
Number of motorcycles (vehicles)	68,625	76,800	[76]
Number of petrol/diesel cars (vehicles)	2,254,538	2,385,800	[76]
Number of electric vehicles (vehicles)	33	38,512	[76]
Road network (km)	55,626	57,077	[5]

Table 3.3: Exogenous variable inputs for both validation and scenario simulations

Variable (units)	Validation Simulation Input	BAU/Scenarios Simulations Input	Source
Population raw growth rate (dimensionless)	2010: 0.007164304 2011: 0.002584954 2012: 0.002653568 2013: 0.003735195 2014: 0.004749794 2015: 0.00589987 2016: 0.003718985 2017: 0.002451703 2018: 0.004633971 2019: 4.94207E-4	2022: 2.6E-4 2023: 5.7E-4 2024: 5.0E-4 2025: 4.0E-4 2026: 3.4E-4 2027: 2.8E-4 2028: 1.3E-4 2029: 4.0E-5 2030: -2.2E-4	[168, 172]
GDP raw growth rate (dimensionless)	2010: 0.022 2011: 0.023 2012: 0.013 2013: 0.025 2014: 0.031 2015: 0.011 2016: 0.003 2017: 0.027 2018: 0.004 2019: 0.011	2022: -0.001 2023: 0.004 2024: 0.008 2025: 0.011 2026: 0.013 2027: 0.013 2028: 0.014 2029: 0.015 2030: 0.015	[167, 173]

Continued on next page...

Variable (units)	Validation Simulation Input	BAU/Scenarios Simulations Input	Source
Distance travelled by buses (km)	340000000 + ((bus modal shift × car distance travelled)/36)	340000000 + ((bus modal shift × car distance travelled)/36)	[5, 169]
Motorcycle carbon emission factor (kgCO_2/km)	0.11367	0.11367	[162]
Petrol/diesel car carbon emission factor (kgCO_2/km)	0.1748	0.1748	[162]
Electric vehicle carbon emission factor (kgCO_2/km)	0.0626342	0.00981765	[74, 75]
Bus carbon emission factor (kgCO_2/km)	1.3	1.3	[174]
Electric bus carbon emission factor (kgCO_2/km)	0.46926	0.07375	[74, 164]

3.2.3 Modelling Scenarios

The model was used to make future predictions under different scenarios for the period 2022 to 2030, with 2022 being taken as the start point as this was the most recent data available. Alongside a Business As Usual (BAU) scenario base case, which assumes no further intervention is taken, four additional scenario components were devised and named ‘A’, ‘B’, ‘C’ and ‘D’. These components were informed by aspirations outlined in Scottish Government policy. Table 3.4 describes each component and provides details of their policy foundations.

Table 3.4: Interventions considered and the policy documents that informed them

Scenario Component/Intervention	Description	Policy Foundation
‘A’ - Active travel	All car journeys under 10km are now completed by active travel	Shorter journeys should ideally be made via active travel, as set out by the National Transport Strategy [18]
‘B’ - Car to bus	All car journeys between 10km and 40km are now completed by bus	Medium-length journeys should ideally be made via public transport, as set out by the National Transport Strategy [18]
‘C’ - Bus electrification	60% of buses are electric by 2024	The majority of buses should be zero emission by 2024, as set out by the National Transport Strategy [18]
‘D’ - EV transition	There is a 50% reduction in the number of petrol/diesel cars by 2030 compared to 2022 levels, with all of those petrol/diesel cars being replaced by EVs	The phasing out of half of all fossil-fuelled vehicles should be achieved by 2030 in urban regions, as set out by the Roadmap to Widespread Adoption of Plug-in Vehicles [17]

All scenarios assume steady, incremental progress in achieving the aspirations within the set time frame (i.e. 2022 to 2030). For scenario components ‘A’ and ‘B’, numerical inputs were determined through distributional analysis of data on the proportion of journeys made according to distance travelled and mode from the Scottish Household Survey 2021 [175], with the original data being shown in Table 3.5. The Scottish Household Survey is used by the Scottish Government as a foundation for data-driven policy formulation.

Table 3.5: Data from [175] on average journey distance by mode

Statistic	**Journey distance by car/van as a driver (km)**
Lower decile	1.3
Lower quartile	2.6
Median	6.6
Upper quartile	17.3
Upper decile	36.1
Mean	16.7

Since only distributional data is available, deriving the required relationship follows by first assuming that a more complete version of the dataset of mode and distance travelled shown in Table 3.5 was available (i.e. it was assumed that the distance of every individual journey included in the dataset was known). It was further assumed the data is discretised such that all journeys fall into distinct distance bins, and where the number of journeys in each bin is known. Let the journey distances be denoted $D_1, \dots, D_M$, and the number of journeys in each bin be denoted $N_1, \dots, N_M$, where M is the total number of distance bins. The total distance travelled by all vehicles is then:

$$D_{tot} = \Sigma_{i=1}^{M} N_i D_i \tag{3.1}$$

and the total number of journeys is:

$$N = \Sigma_{i=1}^{M} N_i \tag{3.2}$$

Therefore, the distance travelled for journeys longer than those in the j^{th} bin is:

$$D_{\geq D_j} = D_{tot} - \Sigma_{i=1}^{j} N_i D_i \tag{3.3}$$

Expressing each N_i as a proportion of the total number of journeys:

$$\varphi_i := \frac{N_i}{N} \Rightarrow N_i = N\varphi_i \tag{3.4}$$

and substituting into 3.3:

$$D_{\geq D_j} = D_{tot} - N\Sigma_{i=1}^{j} \varphi_i D_i \tag{3.5}$$

Now, note that N is not explicitly given in the available data. However, it may still be determined. If μ denotes the mean length of a single journey then, by definition:

$$\mu = \frac{D_{tot}}{N} \Rightarrow N = \frac{D_{tot}}{\mu} \tag{3.6}$$

Substituting into the above allows the following to be obtained:

$$D_{\geq D_j} = D_{tot} - \frac{D_{tot}}{\mu}\Sigma_{i=1}^{j} \varphi_i D_i \tag{3.7}$$

$$\Rightarrow D_{\geq D_j} = D_{tot}(1 - \frac{1}{\mu}\Sigma_{i=1}^{j} \varphi_i D_i) \tag{3.8}$$

The proportion of total distance travelled coming from journeys greater than D_j is therefore:

$$1 - \frac{1}{\mu}\Sigma_{i=1}^{j} \varphi_i D_i \tag{3.9}$$

hence, the proportion of total distance travelled coming from journeys less than D_j is:

$$\varphi_{\leq j} = \frac{1}{\mu}\Sigma_{i=1}^{j}\varphi_i D_i \tag{3.10}$$

And the proportion of total distance travelled coming from journeys between D_j and D_k is:

$$\varphi_{(\leq k)} - \varphi_{(\leq j)} \tag{3.11}$$

These quantities may now be resolved, since μ is provided directly by the Scottish Household Survey data, and $\Sigma_{i=1}^{j}\varphi_i D_i$ terms are readily found by interpolation of the distribution described by the Scottish Household Survey report [175]. In this analysis, logarithmic interpolation and discretisation into distance bins of 0.1 km was utilised. The proportion of total distance travelled made by car or van as a driver undertaking journeys less than 10km was found to be 0.1325, and between 10km and 40km was found to be 0.4414. (For a comparison with travel patterns reported in the UK National Travel Survey, see Appendix A).

The 2021 edition of the Scottish Household Survey was used as it provided the latest data, however, it should be noted that the ongoing COVID-19 pandemic had impacts on data collection methods. Additionally, the data used combined both cars and vans (which are not included in the model). It is assumed in scenario components 'A' and 'B' that EVs and petrol/diesel cars complete the same proportion of journeys within the scenario-specific distance brackets.

The inputs for scenario variables are detailed in Table 3.6. For scenario components 'A' and 'B', the values of the active travel modal shift and bus modal shift variables increase in steady increments until the targeted value found using the Scottish Household Survey data (see Table 3.5) as described above (i.e. 0.1325 and 0.4414 respectively) is reached. For scenario component 'C', it was assumed that having electric buses achieve a proportion of 60% of the entire bus fleet in steady growth increments would fulfil the requirement that most buses be zero emission by 2024. A steady increase in proportion of electric buses continues beyond 2024 until all buses are electric in this scenario component. The other scenario components ('A', 'B' and 'D') are targeted to be achieved by 2030 which is the end of the modelling time frame. Therefore, their progression beyond this point is not considered. For scenario component 'D' the number of petrol/diesel cars was decreased in steady increments until a 50% reduction was achieved in 2030, compared to a 2022 baseline. The incremental reductions in petrol/diesel cars were added to the 'Number of EVs' to simulate the replacement of these petrol/diesel cars with EVs. Although the government aspiration [17] specifies the targeted phasing out of petrol/diesel cars will be focused in urban localities, there are indications in other policy documentation [71] that it is the ambition of the Scottish Government to phase out the overall need for new petrol/diesel cars by 2030. Therefore, the modelled scenario accounts for a 50% reduction in petrol/diesel cars across Scotland as a whole. Note that when scenario component D is being simulated, the model equation for the 'Number of petrol/diesel cars' variable must be zeroed. For the BAU and scenario simulations 'raw GDP growth rate' variable input, there was no data available for 2030, therefore it was assumed that the 2030 GDP growth would remain consistent with the 2029 value.

Table 3.6: Inputs for scenario variables

Scenario Variable	Input
Active travel modal shift	2022: 0.014724125
	2023: 0.02944825
	2024: 0.044172375
	2025: 0.0588965
	2026: 0.073620625
	2027: 0.08834475
	2028: 0.103068875
	2029: 0.117793
	2030: 0.132517125
Bus modal shift	2022: 0.049048778
	2023: 0.098097556
	2024: 0.147146333
	2025: 0.196195111
	2026: 0.245243889
	2027: 0.294292667
	2028: 0.343341444
	2029: 0.392390222
	2030: 0.441439

Continued on next page...

Scenario Variable	Input
Proportion of electric buses	2022: 0.2
	2023: 0.4
	2024: 0.6
	2025: 0.8
	2026: 1
	2027: 1
	2028: 1
	2029: 1
	2030: 1
Electric vehicle shift	2022: 149112.5
	2023: 149112.5
	2024: 149112.5
	2025: 149112.5
	2026: 149112.5
	2027: 149112.5
	2028: 149112.5
	2029: 149112.5
	2030: 149112.5

Continued on next page...

Scenario Variable	Input
Petrol/diesel car shift	2022: -149112.5
	2023: -149112.5
	2024: -149112.5
	2025: -149112.5
	2026: -149112.5
	2027: -149112.5
	2028: -149112.5
	2029: -149112.5
	2030: -149112.5

The fifteen possible combinations of scenario components ‘A’, ‘B’, ‘C’ and ‘D’ (i.e. ‘A’, ‘A+B’, ‘A+B+C’ etc.) were applied to the model. The efficacy of each scenario set was compared to a targeted value of a 56% reduction in emissions of the modes considered in the system, as required by the government mandated target [10]. The contribution of the modes included in the model to the overall transport emissions in 1990 [176] is shown in Table 3.7.

Table 3.7: Data from [176] on the contribution of modes included in the model to transport emissions in 1990

Mode	**Contribution to overall transport emissions**
Petrol/diesel cars	63%
Motorcycles	6%
Buses	0.4%
Total	**69.4%**

The emissions of the modes included in the model in 1990 were therefore calculated using Equation 3.12, where E_{m1990} is the emissions of modes included in the model in 1990, and $E_{tot1990}$ is the total transport emissions in 1990, which is equal to 9.2 Megatonnes of CO_2 (MtCO_2) [176]. $E_{tot1990}$ is multiplied by the proportion of emissions that the modes included in the model are responsible for, as detailed in Table 3.7.

$$E_{m1990} = E_{tot1990} \times 0.694 \tag{3.12}$$

The targeted value of emissions of modes included in the model in line with the 56% reduction was then calculated using Equation 3.13, Where T_e is the targeted value for emissions by 2030.

$$T_e = E_{m1990} \times 0.56 \tag{3.13}$$

The value found for targeted emissions upon achievement of the reduction goal was 2.81 MtCO_2.

Additionally, the targeted value for a 20% reduction in car kilometres travelled by 2030, compared to a 2019 baseline was calculated. Equation 3.14 (where T_d is the targeted car distance travelled by 2030, d_{2019} is the car distance travelled in 2019, and t_{red} is the targeted reduction factor (i.e. 20% or 0.2)) was used to determine the targeted value for car kilometres travelled in line with the 20% reduction, with the reported value of 36,747 million km for car kilometres travelled in Scotland, 2019 [5].

$$T_d = d_{2019} \times (1 - t_{red}) \tag{3.14}$$

The value found for targeted car distance travelled upon achievement of the reduction goal was 29,397.6 million kilometres.

3.2.4 Model Validation

The model was validated by conducting a historical consistency test, comparing simulated values with actual recorded data for the period 2010 to 2019. The years 2020 and 2021 were excluded from the model validation test time-period as during these years, fundamental relationships (e.g. the relationship between GDP and population) broke down due to the outbreak and impact of the COVID-19 pandemic.

On completing the 2010 to 2019 simulation, the mean absolute percentage error was used to compare the simulated and true values, allowing for the quantification of modelling errors. The mean absolute percentage error is given by Equation 3.15 where N is the number of observations, A_t is the actual reported historical value, and M_t is the modelled value given by the system dynamics simulation.

$$MeanAbsolutePercentageError = \frac{1}{N}\Sigma_{t=1}^{N}|\frac{(A_t - M_t)}{A_t}| \tag{3.15}$$

The maximum percentage error was also calculated. As mentioned, sources of the historical data, which was used to inform the model structure and validate the model, and the stock and exogenous variable inputs for the model validation are given in Tables 3.1, 3.2 and 3.3 respectively. No scenario influences (on the number of EVs, distance travelled by cars/active travel/bus or the proportion of electric buses) were present during model validation. The scenario variables, as outlined in Figure 3.2 were inactive throughout the model validation (i.e. their inputs were set to 0 instead of the inputs outlined in Table 3.6).

3.2.5 Model Sensitivity Testing

A sensitivity test was conducted to test the model's response to small changes in the inputs. Scenario 'A' inputs were varied such that the car journeys to be modal shifted to active travel were all those under 5km, to allow results for car kilometres travelled and travel emissions to be compared with the original scenario 'A' where the cut-off was 10km. Similarly, scenario 'D' inputs were varied such that the petrol and diesel cars to be shifted to EVs were 10% higher and lower than the original inputs for scenario 'D'. These variables were chosen to be varied due to the direct influence they have on the key modelling outputs and their specific relevance to policy intervention. A sensitivity test is an important procedure for investigating the robustness of the model and ensuring small changes in inputs do not give radically different results. For the model to be considered reliable, the small changes in inputs should give stable or predictable changes in results.

3.2.6 Limitations

There are limitations and considerations associated with the validated system dynamics modelling framework which should be kept in mind when interpreting these results. These will be summarised here for clarity.

Model set-up: Although historically recorded data for car distance travelled was available for Scotland, no breakdown was given for the distance travelled by petrol/diesel cars and EVs. Therefore, it was assumed that the proportion of each car type (EV and petrol/diesel cars) corresponds to their share of the total car kilometres that each car type drove. Data on licensed vehicles was used to inform vehicle stocks, however, it is possible that there are vehicles licensed in Scotland that are operated outwith Scottish national borders. Equally, there may be vehicles licensed in other UK nations being operated within Scotland. Average vehicle size was assumed and car occupancy and vehicle efficiency were assumed to be constant throughout the modelling timeframe. Offshore GDP and vans, hybrid cars and range-extended EVs were excluded from the model. In calibrating the modelling equations to provide the lowest error (as outlined in Section 3.2.2), it is possible that the risk of overfitting is increased. However, the fact that the model can be termed as a small/mini model (as mentioned in Section 2.2.1) with a minimal number of variables can mitigate the overfitting risk. In the future, when more data pertaining to the variables in the model becomes available, the processes outlined in Section 3.2 could be repeated to potentially provide a more accurate modelling framework informed by more data.

Scenario modelling: First, while vans were excluded from the model, data on car and van journey distances (given in Table 3.5) was used to inform modal shift variables (as outlined in Section 3.2.3). This data was sourced from the 2021 Scottish Household Survey, featuring the latest available figures but employing a different data collection method due to the COVID-19 pandemic. A key disparity between the 2021 Scottish Household Survey and those conducted prior to the pandemic is the data sample size. However, the 2021 sample size was only 6% smaller than the year with the smallest sample size pre-pandemic. Furthermore, when comparing the results for journey distance, the values for the 2021 Scottish Household Survey were relatively in line with pre-pandemic versions. Regarding the modelled scenarios, all were informed by Scottish Government planned interventions [17, 18]. However, it is important to note that not all individuals may be able to complete car journeys under 10km via active travel, as suggested by intervention ‘A’, particularly those individuals with mobility problems. Additionally, intervention ‘C’ modelled an increasing proportion of electric buses beyond 2024, aiming for full fleet electrification by 2026. Yet, practical challenges, such as battery degradation and the inability of buses to serve routes due to restricted range [169], could hinder this transition. Regarding intervention ’D’, the Switched On Scotland policy document [17] outlines that many of the petrol/diesel cars that are eliminated will be replaced by EVs, however, this modelling assumes that all petrol/diesel cars eliminated will be replaced by EVs. All scenarios assume steady, incremental progress in achieving the aspirations within the modelling time frame. The present chapter does not consider any impact that the modal shifting behaviour changes modelled may have on car ownership. Additionally, it does not consider how users make the mode choices that would facilitate the modal shifts considered in the modelling scenarios. Further work could consider potential interactions between modal shifting and car ownership and consider supporting policies and actions that could influence mode choice to achieve the modal shifts.

Emissions targets: The calculation of the emission reduction target threshold presented in this chapter (see Section 3.2.3), assumes a 56% reduction in emissions for the transport modes included in the model (cars, buses and motorcycles). Therefore, it was assumed that these modes are expected individually to achieve a 56% reduction [10]. In practice, other transport segments like air, maritime, and freight might contribute significantly to achieving the overall emission reduction target, potentially reducing the burden on the road passenger modes. Despite this, given road transport’s significant contribution to overall transport emissions [5], this sector will remain a key target of emission reduction efforts and equally, could play a major role in achieving the target. Future research could investigate the utility of a specific emissions target for road passenger transport and determine an appropriate threshold.

3.3 Results and Discussion

To investigate the potential efficacy of and likelihood that planned interventions can achieve government mandated transport emission reduction targets in Scotland, a system dynamics modelling framework and scenario-based analysis has been undertaken, as described in Section 3.2. The following subsections detail the results obtained for the model validation test; the model sensitivity test; the total emissions of the road passenger transport system and the car kilometres travelled in Scotland under the modelled BAU scenario and scenarios involving sustainable transport interventions.

3.3.1 Model Validation

Table 3.8 gives the mean absolute percentage error found for each stock variable in the model validation test, which compared modelled values against actual recorded data (the sources of which can be found in Table 3.1) across the period 2010 to 2019. All mean absolute percentage error values are below 10% and so the model is considered valid. Figure 3.3 also provides plots of the modelled values for the stock variables in the validation simulation compared to the actual reported values for the number of petrol/diesel cars [76], the number of motorcycles [76], the number of EVs [76], road network [5], population [168] and GDP [167] across the years 2010 to 2019.

The model has therefore been validated across a nine-year time period (i.e. 2010 to 2019). While the low mean absolute percentage error values indicate that the modelling framework is a good fit and appropriate for the application of the future simulations across an eight-year period (i.e. 2022 to 2030), it should be noted that application to larger future projections that go beyond 2030 may give more significant error.

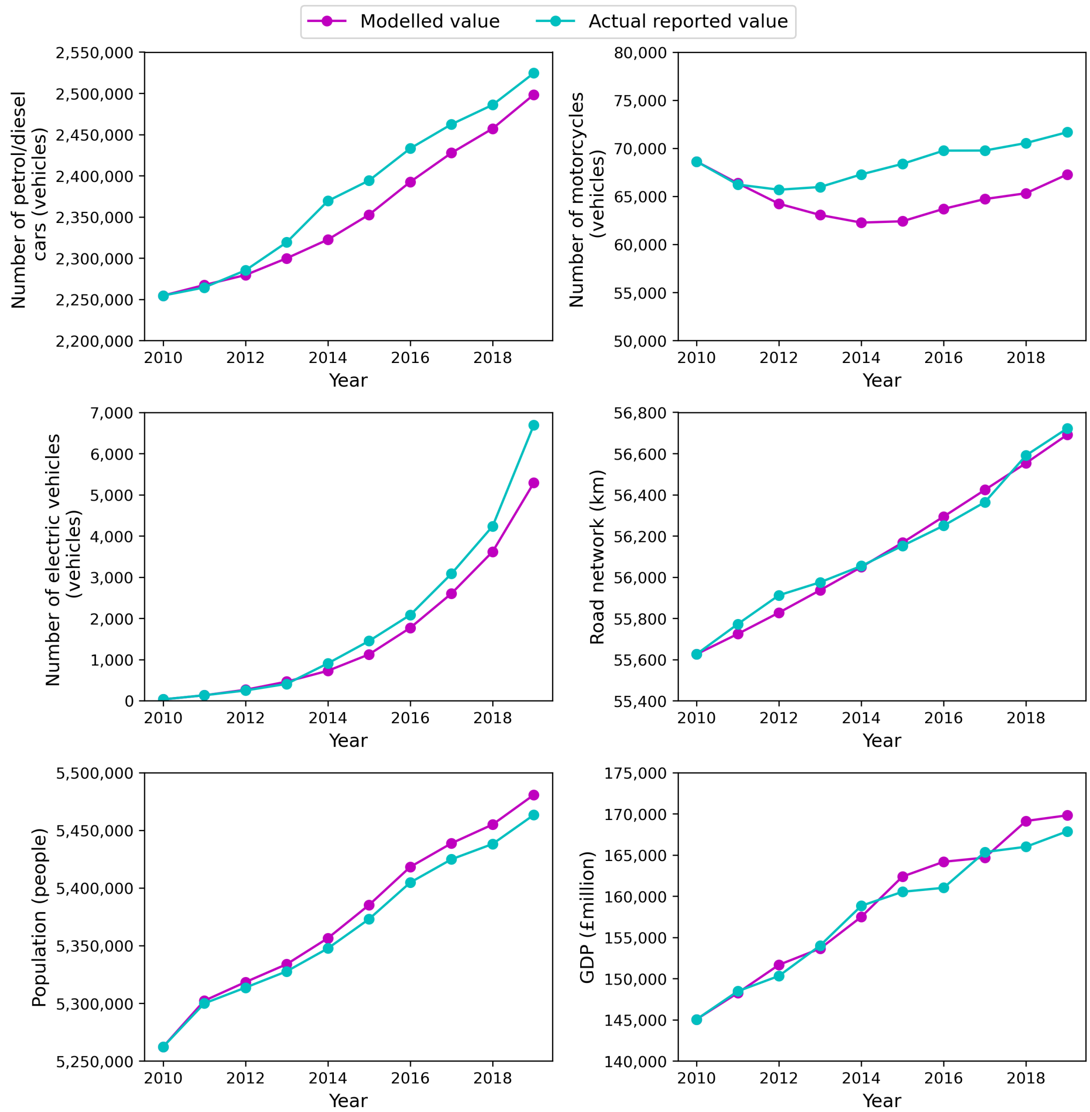

Figure 3.3: Modelled values for stock variables in the validation simulation compared to actual reported values

The maximum absolute percentage error is also provided for context to give an indication of the upper limit of the model's inaccuracy. Similarly, the maximum absolute percentage error is below 10% for all stock variables, with the exception of the 'Number of EVs' variable. This highlights that although the model can generally accurately forecast the 'Number of EVs' (as evidenced by the low mean absolute percentage error value), there are occasions where the modelled values could have higher error.

Table 3.8: Validation test results of Mean Absolute Percentage Errors and Maximum Absolute Percentage Errors for stock variables

Variable	Mean Absolute Percentage Error	Maximum Absolute Percentage Error
Number of petrol/diesel cars	0.99%	1.98%
Number of motorcycles	5.20%	8.73%
Number of electric vehicles	8.88%	22.45%
Road network	0.02%	0.15%
Population	0.18%	0.32%
GDP	0.54%	1.96%

3.3.2 Model Sensitivity

Tables 3.9 and 3.10 give the results of the sensitivity test. The small changes in variable inputs resulted in steady, predictable changes in outputs. A more intensive transition to EVs resulted in reduced emissions, as expected. Similarly, a less intensive transition to EVs resulted in increased emissions. In terms of adjusting the journey distance to be modal shifted to active travel, a reduction in car kilometres to be modal shifted resulted in increased travel emissions and car kilometres travelled, also as expected. Therefore, the model may be considered appropriately robust since input and modal shift differences have been shown to influence predictions in a steady and predictable manner that does not dramatically change the interpretation or conclusions of these analyses.

3.3.3 Total Road Passenger Transport Emissions

The model predicts the emissions of road passenger transport in Scotland between 2022 and 2030 under the implementation of the interventions considered in this chapter (see Section 3.2.3). The fifteen possible combinations of interventions 'A' (active travel), 'B'

Table 3.9: Sensitivity test results when inputs for scenario component 'D' were varied

	2030 Transport Emissions (MtCO_2	**Percentage Difference with respect to 'D' 2030 Emissions**
D	4.523	-
+10%	4.302	-4.878%
-10%	4.743	4.878%

Table 3.10: Sensitivity test results when inputs for scenario component 'A' were varied

	2030 Transport Emissions (MtCO_2)	**2030 Car Distance Travelled (million vehicle km)**	**Percentage Difference with respect to 'A' 2030 Emissions**	**Percentage Difference with respect to 'A' 2030 Car Kilometres**
A	7.686	49,834	-	-
5km modal shift	8.293	54,042	7.888%	8.443%

(car to bus), 'C' (bus electrification) and 'D' (EV transition) have been grouped in result sets of single interventions, double interventions, and triple/quadruple interventions to communicate the result more clearly. The BAU base case is included in each result set for reference. The emissions of each scenario set are compared to a 56% reduction compared to 1990 levels (as mandated by the Scottish Government [10], see Section 3.2.3) and this target threshold is represented on each plot by a black horizontal line.

Figure 3.4 shows the application of each scenario component in isolation. The model predicts all interventions will facilitate a decrease in emissions with respect to the BAU case, but only scenario components 'B' and 'D' are projected to give a decrease in emissions over time. This implies that encouraging modal shifting to buses for medium-length car journeys and transitioning away from petrol/diesel cars to EVs are likely to be the most effective intervention strategies.

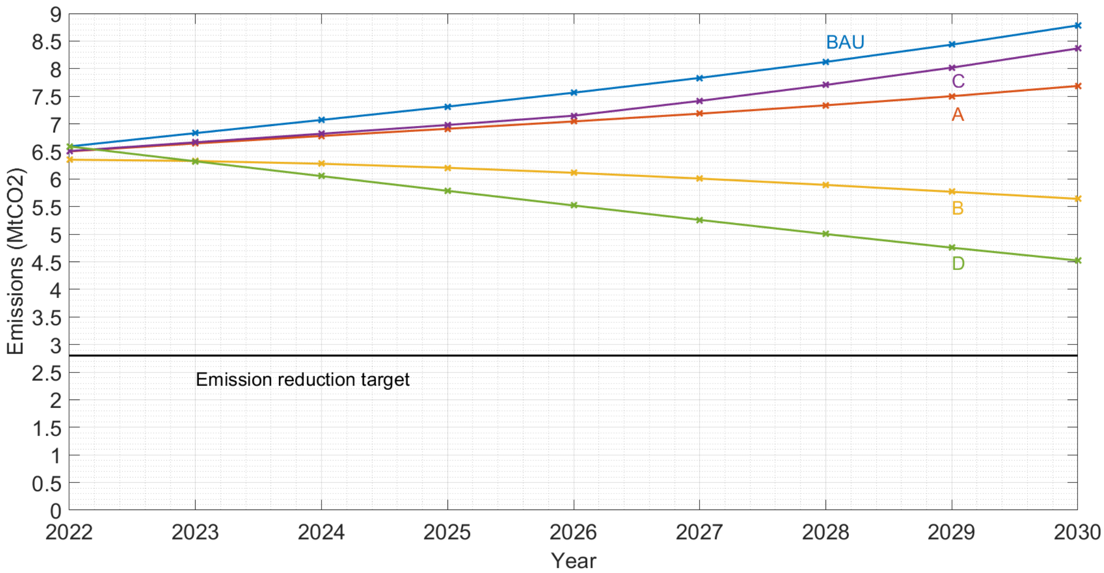

Figure 3.4: Emissions trends predicted by the model under implementation of individual interventions

By 2030, it is predicted that there will be 8.8MtCO_2 of emissions from road passenger transport in Scotland under the BAU base case. Scenario components 'A', 'B', 'C' and 'D' are projected to give emission reductions of 12.5%, 35.8%, 4.7% and 48.5% respectively, compared to the 2030 BAU emissions predicted by the model. Scenario component 'D' initially has a more modest impact on emissions but this quickly accelerates over time to give the greatest emission reduction compared to BAU. Scenario components 'B' and 'D' are forecast to give emission reductions of 11.7% and 29.2% respectively with respect to the road passenger transport emissions in 1990. As demonstrated by Figure 3.4, no individual intervention achieves the 56% reduction in emissions target, indicating that tackling transport emissions is not a single-solution problem.

Figure 3.5 shows the results of the application of scenarios grouped in pairs. The model forecasts greater emission reductions in these cases compared to application of individual scenario components, as would perhaps be expected. Almost all pairs of scenario components are projected to facilitate a decrease in emissions with respect to time, however there are still no cases where the emission reduction is predicted to be achieved. Scenario 'A+C' is not predicted to drive a decrease in emissions over time

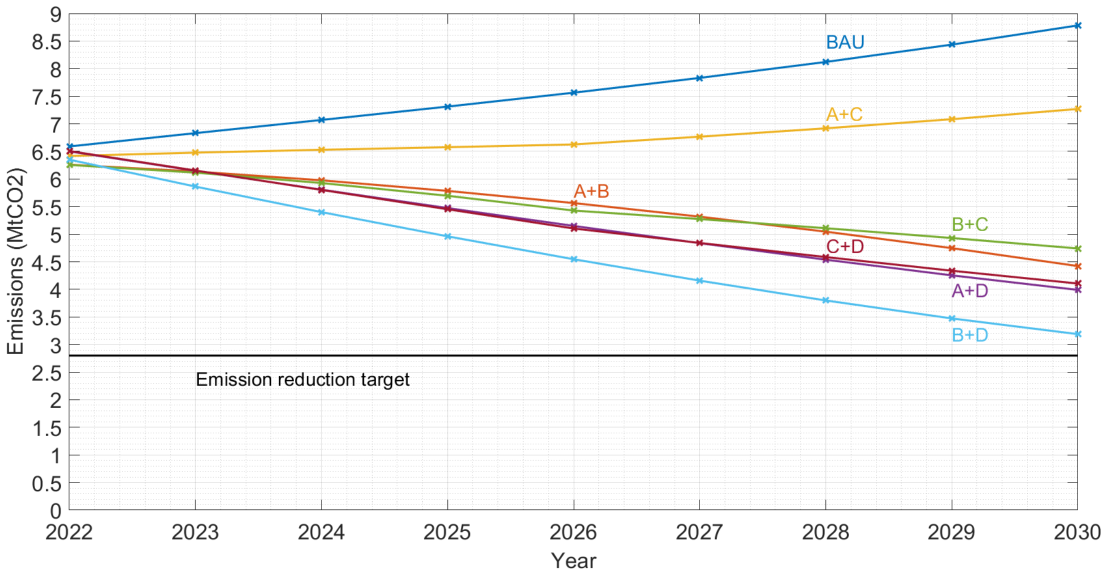

Figure 3.5: Emissions trends predicted by the model under implementation of pairs of interventions

and is likely to give the smallest decrease in emissions with respect to the BAU base case, specifically a 17.2% decrease. Meanwhile, scenario 'B+D' is projected to give the most significant decrease in emissions, 63.7% with respect to BAU, and the remaining scenarios (i.e. 'B+C', 'A+B', 'C+D' and 'A+D') are forecast to result in between 46% and 54.6% emission reductions compared to the BAU base case.

Figure 3.6 illustrates that groupings of three and four interventions are predicted to give greater emission reductions again, in comparison to single and pairs of interventions. All scenarios in this instance are forecasted to facilitate a decrease in emissions with respect to time and the combination of all four scenario components is predicted to give the largest emission reduction, unsurprisingly. The model projects that in three cases, 'A+B+D', 'B+C+D' and 'A+B+C+D', the 56% emission reduction target is met. These combined scenarios were predicted to enable 70.9%, 73.2% and 79.3% emission reductions compared to BAU, and 60%, 63.1% and 71.5% reductions with respect to road passenger transport emissions in 1990 respectively. The less impactful scenario combinations, 'A+B+C' and 'A+C+D', were predicted to achieve similar emission reductions, namely 58.6% and 59.3% reductions with respect to the BAU base case and

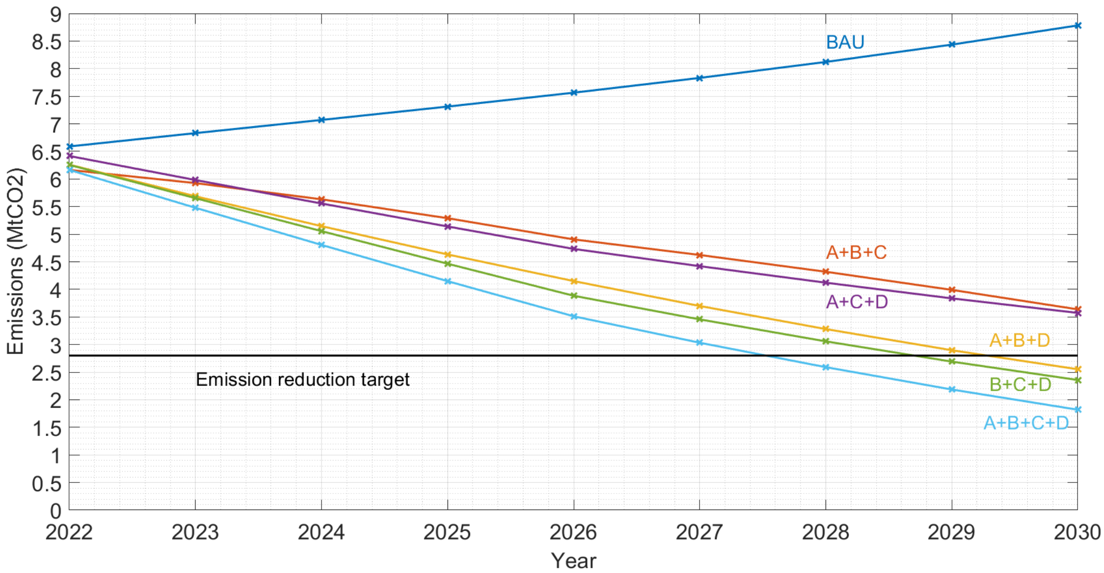

Figure 3.6: Emissions trends predicted by the model under implementation of groups of three and four interventions

43% and 44% reductions with respect to 1990 levels.

The requirement for three or more interventions to meet the emission reduction target, as illustrated by Figures 3.4, 3.5 and 3.6, confirms that a single intervention is likely to be insufficient in tackling transport emissions and a broad package of interventions is needed. This corroborates the findings of previous works [23, 65] which emphasise the need for implementation of multiple measures to achieve effective emission reductions. In the instances where the emission reduction target is met, interventions 'B' and 'D' are the only ones to be present in each case. This indicates these interventions could have a critical role and further emphasises their particular effectiveness. Regarding interventions 'A' and 'C', their impact on emissions was projected to be less significant compared to interventions 'B' and 'D'. However, considering the prediction that at least three interventions are necessary to meet the emission reduction target, their contribution was still found to be important.

3.3.4 Car Kilometres Travelled

The model also forecasts the car kilometres travelled in Scotland between 2022 and 2030 for each possible scenario combination. The results for the total distance travelled by car under all fifteen scenario component combinations and the BAU case are shown in Figure 3.7. Some scenario combinations feature the same car kilometres travelled, primarily because intervention 'C' does not feature any change in car kilometres, and so have been grouped accordingly. The car kilometres travelled in each scenario set are compared to a 20% reduction compared to 2019 levels (as mandated by the Scottish Government [11], see Section 3.2.3) and this target threshold is represented on the result plot by a black horizontal line.

Like emissions, all combinations of interventions are projected to result in a decrease in car kilometres with respect to the BAU case, but not all are predicted to give a decrease over time. Namely, scenarios 'B', 'B+C', 'B+D', 'B+C+D', 'A+B', 'A+B+C', 'A+B+D' and 'A+B+C+D' are those projected to give a decrease in car kilometres over time, and only scenarios 'B+D', 'B+C+D', 'A+B', 'A+B+C', 'A+B+D' and 'A+B+C+D' are forecasted to achieve the 20% reduction in car kilometres. The scenarios that were predicted to achieve the target were forecast to enable reductions in car kilometres between 25% and 42.8% with respect to 2019 levels, and 52% and 63.4% with respect to BAU in 2030. The scenarios that were not projected to meet the target were predicted to facilitate a reduction in car kilometres between 13.3% and 44.1% compared to BAU. Comparing these scenarios to 2019 levels for car kilometres, the predicted percentage change ranged from a 35% increase to a 12.7% decrease in car kilometres travelled.

A combination of at least two scenario components is required to meet the car kilometre reduction target, and component 'B' is the only intervention to be present in all scenarios predicted to achieve the target. This again highlights the potential effectiveness of intervention 'B' in facilitating both emission and car kilometre reductions in line with government targets, while also emphasising the need for a comprehensive package of interventions rather than a single solution. It is notable that all scenarios predicted

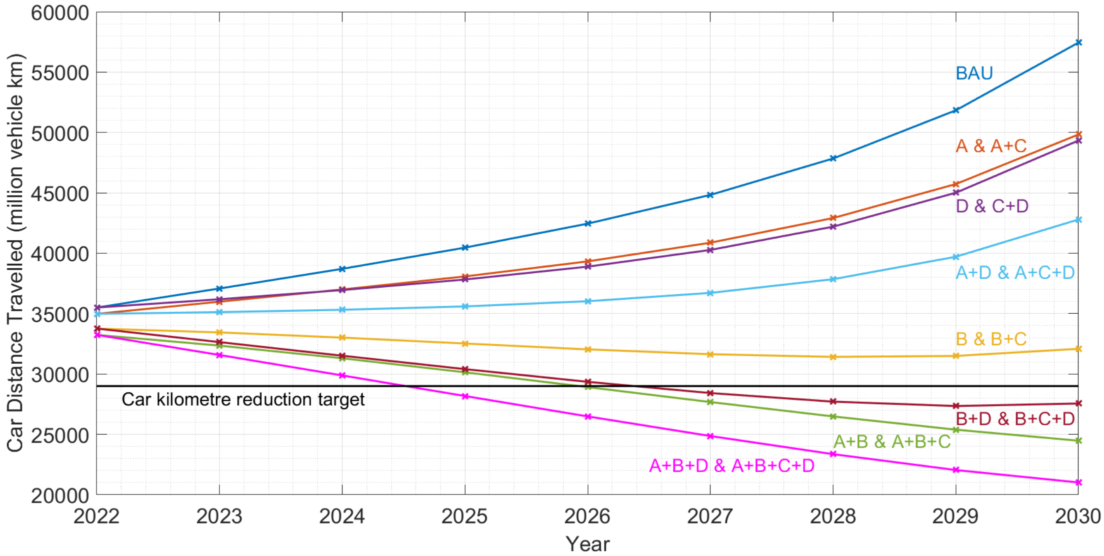

Figure 3.7: Car kilometre trends predicted by the model under implementation of all possible combinations of interventions

to achieve the emission reduction target (see Figure 3.6) also meet the car kilometre reduction target (see Figure 3.7). However, there are additional scenarios that meet the car kilometre reduction target while not achieving the emission reduction target. This indicates that reaching the car kilometre reduction target does not necessarily guarantee the achievement of the emission reduction target in Scotland.

Interestingly, intervention 'D', which does not explicitly target car kilometres travelled but rather the EV penetration of the vehicle fleet, was projected to achieve a similar car kilometre reduction to intervention 'A' with respect to BAU. This appears to be due to an overall decrease in car ownership in scenario 'D', with a projected 24.8% reduction in the number of cars by 2030 compared to the BAU base case. This, in turn, is driven by the halting of growth in the petrol/diesel car market. While this is somewhat offset in the model by the increase in EV numbers spurring further growth in the EV market, the overall number of cars remains less than that in the BAU base case. Combined with the significant ability of scenario component 'D' to reduce transport emissions, these results suggest it is a highly impactful intervention. It should, however, be noted that other considered interventions (namely the modal shifts to active travel and bus) provide additional societal benefits in the form of enhanced public health [7] and greater societal equity [9, 50], which intervention 'D' does not inherently provide. These factors should also be considered when undertaking policy decision making.

3.4 Implications for Policy, Practice and Future Work

The results of this chapter give insight into the impact of key interventions, namely modal shifting to more sustainable modes and electrification of bus and private car fleets, on transport emissions. The findings presented have important implications for policy, transport planning and future work. There are subsequent recommendations for critical areas where supporting policy should be focused or enhanced and for ways in which the transport system could be planned and developed in future.

The demonstrated efficacy of modal shifting of medium-length car journeys to buses and the transition to EVs suggests that these should be areas where supporting policy is targeted. The subsequent recommendations made are summarised in Figure 3.8. Scottish Government polices supporting a shift towards EVs have been found to be relatively effective at reducing emissions [71]. However, to fully harness the potential benefits of the EV transition, careful thought will need to be given as to how this transition can be enabled equitably while still prioritising active travel and public transport modes. Key challenges include providing inclusive charging infrastructure [25] (which the Scottish Government have committed to doing in their Vision for Scotland's Public EV Charging Network [26]), reducing the need for car ownership and enhancing infrastructure and services for alternative modes to private cars. It is crucial to distribute public EV charging facilities spatially in a way that encourages active travel or public transport use. For example, charging infrastructure could be situated in a way that encourages 'park and ride' or 'park and stride' behaviour (combining car use with public transport or active travel modes to complete a journey) through strategic placement at locations such as train stations, bus stops or active travel hubs. Selecting suitable charging infrastructure types (i.e. charging speed and power rating), particularly accounting for the ability of grid infrastructure to manage such additional loads will also

Figure 3.8: Summary of the key implications the results of this chapter have for policy and transport planning, providing recommendations to support achievement of the most effective interventions

be a key consideration.

While specific existing policy packages supporting modal shifting in Scotland (e.g. investments in active travel and bus infrastructure, provision of free bus travel for certain age groups) have also been forecast to facilitate emissions reductions in Scotland [71], this study's findings suggest that further enhancing policy support for the modal shifting of medium-length car journeys to bus travel could amplify emission reduction efforts. Investing in the development of MaaS, which has been shown to effectively encourage modal shifting away from the private car and towards public transport [66–68] could be advantageous. The Scottish Government's financial support for a series of individual regional MaaS pilot schemes [63] is a positive step. Investing in the development of a nationwide MaaS programme (or similar system) that interacts or integrates seamlessly with public transport provision across different regions of Scotland, or potentially other UK regions, could help promote modal shifting of medium-length and longer car journeys that may cross regional boundaries.

Furthermore, enhancing public transport provision so that it can rival the private car's sense of autonomy [69] and meet the diverse needs of different groups (e.g. shift workers, those with additional care responsibilities, those who operate at multiple workplaces) who may travel at unconventional times or require unconventional routes, will be key to enabling a modal shift of medium-length car journeys. Addressing other key barriers to public transport that protected groups face (e.g. cost of transport services and experience of transport poverty [52, 53], safety concerns which are disproportionately experienced by certain groups such as women [54]) should be treated as a priority in order to encourage use of this mode, especially for longer journeys.

The important role that the modal shift to active travel and electrification of the bus fleet could play in bolstering the emission reduction impact of other interventions to enable achievement of emissions targets, indicates that policies supporting these interventions remain critical. A significant modal shift towards active travel may prompt an increase in uptake of electric micromobility modes such as electric bicycles and scooters [19], which can pose their own set of challenges [20]. It is crucial that active travel infrastructure is designed to safely accommodate these alongside other active travel modes.

The results of this work also indicate that the car kilometre reduction target is generally a viable strategy for reducing transport emissions, with other works highlighting a reduced car dependency can enable a more equitable transport system [9,50]. However, since achieving the car kilometre reduction target alone may not ensure achievement of emission reduction targets (as discussed in Section 3.3.4), interventions beyond a 20% reduction in car kilometres travelled may be required. Again, the projected efficacy of modal shifting to bus in reducing car kilometres indicates that this intervention warrants robust policy support. Additionally, the car kilometre reduction potentially facilitated by shifting to EVs suggests that policies promoting a reduction in car ownership could facilitate an effective decrease in car kilometres travelled. Such legislation could further support development of zero-emission car clubs in Scotland [62], which are known to reduce personal car ownership [64] and emissions [65], or support MaaS initiatives as an alternative to private car use, though their impact on car ownership remains disputed [68–70].

Further research work is needed to explore the relationship between car ownership and car kilometres travelled in the Scottish context for comprehensive policy recommendations to be developed. Additional research work should consider how to address issues associated with increasing EV uptake in the Scottish context and explore equitable solutions for the evolving demand for energy and charging infrastructure. It is also necessary to explore the feasibility and design of a nationwide MaaS system or multiple localised MaaS systems that are interoperable with their regional counterparts in Scotland. Furthermore, work seeking to determine the most cost-effective and efficient pathways to delivering the specific enhancements to public transport provision mentioned above (i.e. ensuring public transport can meet the diverse needs of different groups, addressing barriers to access such as safety concerns, cost etc.) is warranted. Increased active travel and electrification of the bus fleet are both interventions that will likely contribute to the decarbonisation of the road passenger transport sector, further research on their effective implementation within the Scottish context (and supportive legislation) would therefore be valuable.

Additionally, further research exploring the likelihood and extent to which the behavioural change considered in this chapter (i.e. modal shifting away from the private car and transitioning towards EVs) can be achieved is warranted. Exploration of pathways to enabling these changes such as social marketing programmes and other policy packages could give insight into how these shifts can be effectively delivered. Specifically, further work should explore how mode choice can be effectively influenced by supporting policy to achieve the modal shifts considered in this chapter. Facilitation of a modal shift may be more challenging during wintertime and times of poor weather [177]. Potential seasonal impacts on the achievement of a modal shift in the Scottish context, particularly during the winter months, should also be the subject of future work. The present model could also be expanded and developed to be applicable to other important problem contexts and to give insight into other relationships and complexities in the transport sphere. For example, through addition of further variables, feedback loops and structures, the model could consider concepts such as induced demand and the impact that policy surrounding land use and space allocation given to private mobility, particularly cars, may have on modal shifting. Specifically, modelling induced demand could require a feedback loop featuring road network, travel speed and mode choice variables to capture how additional road kilometres can result in increased travel speeds/reduced journey times which can promote additional car usage [178]. However, such extensions would require additional data and careful model development to ensure the validity of results is not compromised and any limitations can be understood.

In summary, the substantial challenge transport emissions pose to a net zero future in Scotland, and the cumulative nature of emissions, highlight the urgency of achieving reductions soon. Understanding the likely effectiveness of planned interventions in meeting emission targets is critical. Previous studies [23,65] highlight the need for multiple interventions to achieve significant emission reductions, a finding that is strongly supported by this work. The transition to EVs and the modal shifting of medium-length car journeys to bus travel were identified as the most effective interventions. While a 20% reduction in car kilometres travelled has been found to be beneficial for lowering emissions, in isolation it may not guarantee achieving the target of a 56% reduction in emissions.

3.5 Conclusions

This chapter has developed, validated and applied a system dynamics model of the Scottish road passenger transport sector to explore the likely ability of planned interventions to reduce transport emissions in Scotland, in line with government targets. Specific interventions considered were the modal shifting of car journeys under 10km to active travel; the modal shifting of car journeys between 10 and 40km to bus transportation; achieving a 60% electrification of the bus fleet by 2024; and a 50% reduction in petrol/diesel cars by 2030, with these cars being replaced by EVs. The potential contribution these interventions can make towards achieving Scottish Government targets, namely a 56% reduction in transport emissions compared to 1990 and a 20% reduction in car kilometres compared to 2019, was explored. With the 2030 deadline for these targets rapidly approaching, it is pertinent to ensure that planned interventions are fit for purpose and effective.

Results indicated that certain combinations of interventions would be able to achieve the government mandated 56% reduction in emissions by 2030. However, the implementation of at least three interventions was required in each case, highlighting the need for a broad programme of measures. The transition from petrol/diesel cars to EVs and the modal shifting of medium-length car journeys to buses were found to drive the most significant emissions reductions, indicating these are areas where supporting policy should likely be prioritised. Regarding car kilometres travelled, results indicated that the 20% reduction target could also be met by 2030 through certain combinations of interventions. In each case, at least two interventions were required to meet the target, indicating that this too will require a programme of measures rather than a single solution. The modal shifting of medium-length car journeys to buses was again found to be a particularly effective intervention in terms of car kilometre reduction. Furthermore, it was found that while the 20% reduction in car kilometres travelled can facilitate a reduction in emissions, its achievement does not guarantee also achieving the 56% emissions reduction target.

These findings offer insight into the potential effectiveness of planned interventions to achieve meaningful emission reductions and have implications for future research, policy and transport planning. With the predicted efficacy of transitioning to EVs comes a need to ensure such a transition is enabled equitably, whilst still prioritising active travel and public transport modes. Achieving a spatial arrangement of public EV charging infrastructure that encourages use of these other modes, as well as ensuring the resultant changes in demand for energy and charging infrastructure are met equitably, presents a number of challenges and potential issues that require further work to address. Additionally, the likely effectiveness of modal shifting medium-length car journeys to buses indicates that robust policy support for enhancing attractiveness and equitable access to this mode is warranted. Addressing barriers that some groups face to public transport such as safety concerns, cost or lack of service provision were highlighted as being particularly important in this context. Prioritising the interoperability of localised MaaS schemes such that they can interact seamlessly, or aiming for a nationwide MaaS system, may also promote the switching of medium-length or longer car journeys to public transport. As other international governments begin to introduce car kilometre reduction targets and, more broadly, tackle transport emissions as a significant barrier to net zero, it is hoped that the modelling approach and findings of this chapter will also support the development and evaluation of transport policy in a broader international context.

Therefore, in terms of Research Question 1 (as outlined in Chapter 1), this chapter has found that the transition to EVs is likely to be a highly critical intervention in the context of achieving Scottish Government targets. In comparison with the other interventions considered, it was predicted to enable the greatest emission reduction and therefore will likely play a fundamental role in the achievement of a more sustainable transport system in the Scottish context. This highlights the need for an understanding of how an equitable transition to EVs can be supported in Scotland, particularly relating to development of public charging networks that will be critical to enabling those without private charging facilities or those completing longer car journeys to participate in the transition. To inform policy and practice relating to development of public charging in Scotland, it is first necessary to understand the current state of public charging and how it is used, which will be the focus of Chapter 4.

Chapter 4

Location and Utilisation of Existing Charging Provision via ChargePlace Scotland

4.1 Introduction

As found in Chapter 3, the transition to EVs was predicted to be the most effective intervention in terms of reducing transport emissions in the Scottish context. Therefore, supporting an equitable transition to EVs will be critical to enabling achievement of government targets. However, as discussed in Section 1.2, the realisation of an inclusive transition to EVs requires that EV charging infrastructure be available and accessible, and public charging infrastructure will play a particularly important role.

Development of the public charging network in Scotland will involve consideration of many factors including charging tariffs, power rating of chargers and charger location. 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 chapter, 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 address Research Question 2 (as outlined in Chapter 1) - *What is the current state of Scotland's public EV charging network, and what are the related implications for realising an equitable transition to EVs?* Additionally, the following sub-questions will be explored:

a) Where are Scotland's public EV chargers currently located?

b) When are Scotland's public EV chargers typically used?

c) What impact does the introduction of tariffs have on Scottish public EV charger usage?

d) What characteristics do the most utilised public EV chargers in Scotland have?

In addressing these research questions, this chapter 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 chapter 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 chapter is structured as follows: Section 4.2 outlines the methodology and details the developed dataset; Section 4.3 details and discusses the results of the analysis; Section 4.4 provides a discussion of the implications the results have for policy, transport planning, and future work; and Section 4.5 concludes the chapter.

4.2 Methodology

The research methodology falls into two distinct parts, dataset development and dataset analysis. The current section will detail each in turn. Section 4.2.1 outlines dataset development. As stated in the sub-questions detailed in Section 4.1, this chapter 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 4.2.1 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 4.2.2 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.

4.2.1 Dataset Development

Firstly, raw data from ChargePlace Scotland [131] 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 [179] were removed. Furthermore, any charging sessions costing the user more than the most expensive tariff (plus the current overstay fee [180]) 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 [142], the Scottish Index of Multiple Deprivation, and the Geographical Accessibility Index [141] were added to the dataset using geospatial techniques. As described in Section 2.5, 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 [181] was then used to assign each charger its corresponding Urban Rural Classification, Scottish In-

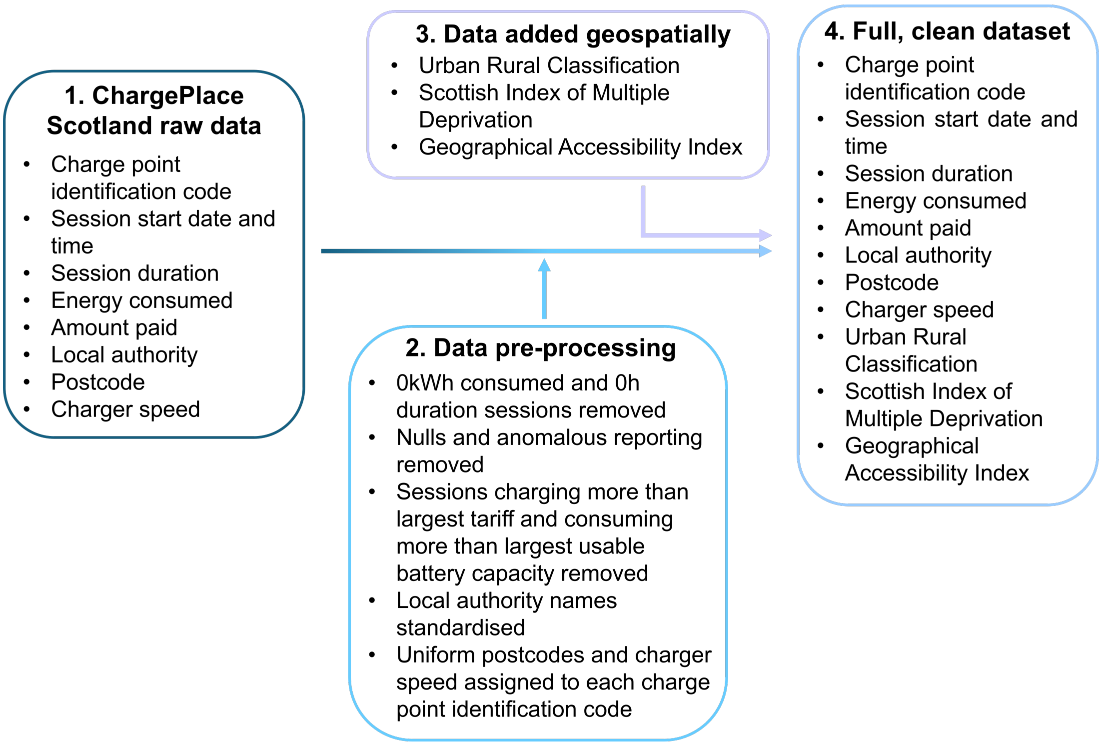

Figure 4.1: Flowchart outlining the dataset creation process, including cleansing of raw EV charging session data from ChargePlace Scotland and the addition of supplementary geographical indicators

dex of Multiple Deprivation, and Geographical Accessibility Index. Spatial joining allows data to be joined based upon their spatial locations [182]. Figure 4.1 provides a graphical summary of the dataset creation process.

4.2.2 Dataset Analysis

The dataset analysis falls into four categories, each addressing one of the research sub-questions outlined in Section 4.1. Figure 4.2 details the four categories of dataset analysis and the analysis process that is related to each sub-question. A description of each analysis is provided below.

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

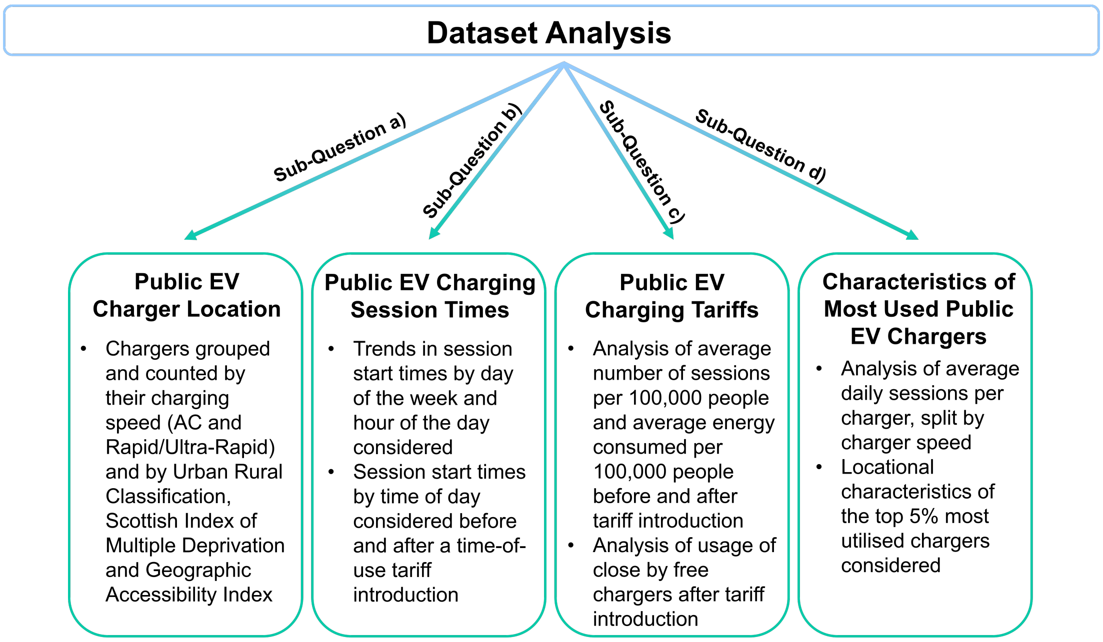

Figure 4.2: Flowchart detailing the dataset analysis processes conducted and their related research sub-questions that they are conducted to address

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 [183]. 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.

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 2.4, 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 [184] 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.

Public EV Charging Tariffs: For the twelve Scottish local authorities that introduced EV charging tariffs within the dataset time period (as described in Section 2.4), 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 above, 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 2.4, although there are multiple different charger operators on the ChargePlace Scotland network, chargers are predominantly owned and operated by local councils [42].

Characteristics of the Most Used 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. Specifically, it is possible that when an individual charger is free to use it experiences increased utilisation as there is no financial penalty or cost incurred. Therefore, including only paid-for sessions avoids the possibility that the utilisation of a charger is overestimated due to inclusion of free sessions.

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.

4.2.3 Limitations

There are limitations associated with the above research methodology which are summarised in this section for clarity.

Dataset development: Firstly, although measures were taken to improve data quality, as described in Section 4.2.1, 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 4.2.1, 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 [185]. 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 [186]. Therefore, there may be some instances of incorrectly allocated data when using the described geospatial techniques.

Dataset analysis: Regarding the 'Public EV Charging Tariffs' analysis (see Figure 4.2), as mentioned in Section 4.2.2, 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 'Characteristics of the Most Used Chargers' analysis (see Figure 4.2) outlined in Section 4.2.2, 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 ('Characteristics of the Most Used Chargers') 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.

Socioeconomic indicators: 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 2.5, can give a holistic understanding of deprivation at a detailed level, but it cannot give an indication of affluence [187]. 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 [141]. 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 [188, 189]. 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 [144]. The limitations of these indicators should be kept in mind when considering the results of the analyses which include them.

4.3 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 4.2. 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 4.4.

4.3.1 Dataset Overview

Table 4.1 details the number of charging sessions and unique chargers included in the dataset before and after the data pre-processing measures described in Section 4.2.1 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 4.2.2.

Table 4.1 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 4.2 also provides a breakdown of the proportion of the data before cleaning that were made up of the various outliers removed (as described in Section 4.2.1).

Additionally, 77% of the chargers in the dataset were found to be AC chargers, with the remaining 23% being rapid/ultra-rapid chargers. Figure 4.3 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 4.4. There are also notable dips in the number of sessions across the festive period surrounding Christmas and New Year.

Table 4.1: Overview of the number of EV charging sessions included in the dataset before and after data cleaning 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 (paid and free)	3,120,526	3,543
All sessions after data cleansing (paid and free)	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 only sessions	1,514,981	2,426

Table 4.2: Breakdown of the proportion of uncleaned data made up by anomalies outlined in Section 4.2.1

Anomaly	Proportion of uncleaned data
Duration 00:00:00	0.7%
Sessions containing nulls	1.7%
Sessions consuming 0kWh	5.9%
Sessions consuming greater than what would be compatible with useable battery capacity	0.01%
Sessions costing greater than most expensive tariff	0.2%
Dates with anomalous reporting	5.3%

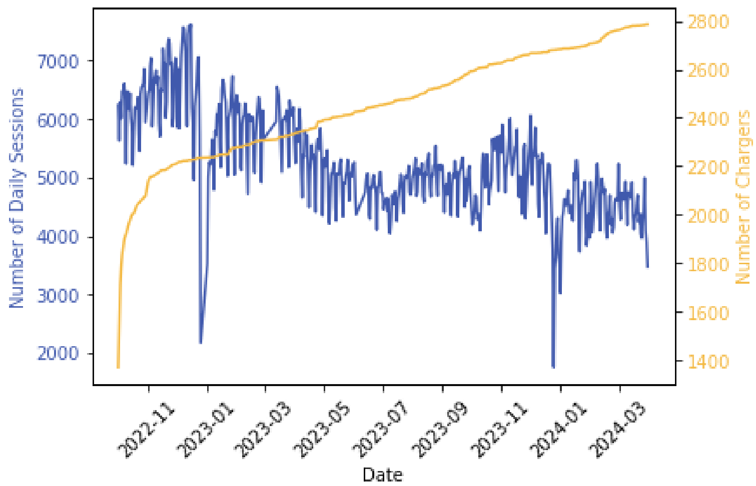

Figure 4.3: The total number of EV charging sessions taking place on all chargers (AC and rapid) on the ChargePlace Scotland public network between October 2022 and March 2024

4.3.2 Public Electric Vehicle 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 4.4 shows the absolute number of AC and rapid/ultra-rapid chargers in each Urban Rural Classification within the constructed dataset, and Figure 4.5 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 [190]), 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 4.4.

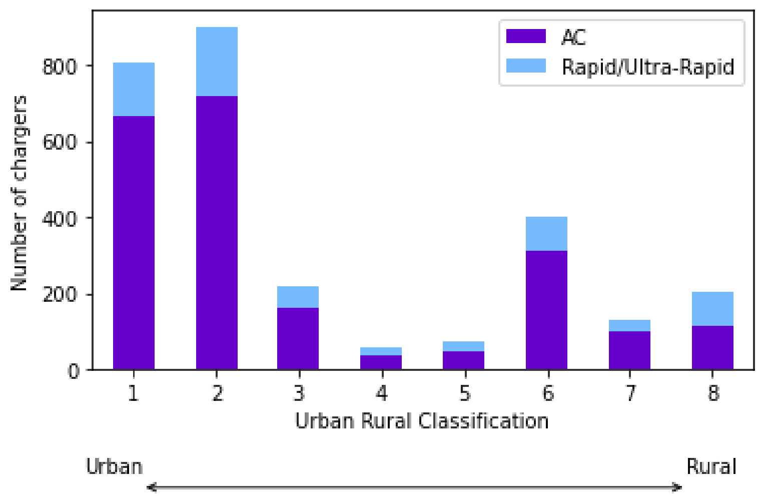

Figure 4.4: The absolute number of EV chargers on the ChargePlace Scotland public network found in each Urban Rural Classification, where a lower classification value generally indicates a more urban area, and a higher value generally indicates a more rural area

Figure 4.4 shows that the absolute number of chargers is generally concentrated in more urban areas. There are 1,929 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

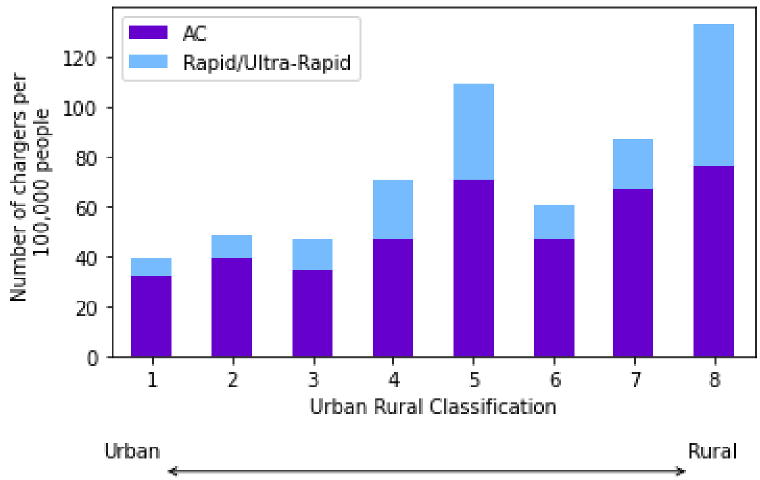

Figure 4.5: The number of EV chargers per 100,000 people on the ChargePlace Scotland public network found in each Urban Rural Classification, where a lower classification value generally indicates a more urban area, and a higher value generally indicates a more rural area

chargers.

However, Figure 4.5 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 2.5, 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) [145]. 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

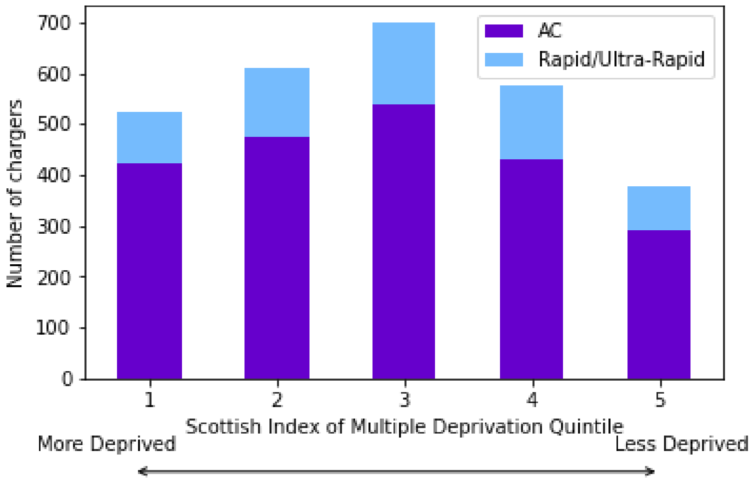

Figure 4.6: The absolute number of EV chargers on the ChargePlace Scotland public network found in each Scottish Index of Multiple Deprivation quintile, where a lower quintile generally indicates a more deprived area, and a higher quintile generally indicates a less deprived area

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 [145], as mentioned in Section 2.5.

Figures 4.6 and 4.7 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 although plots of the number of chargers per 100,000 people are given in Figures B.1 and B.2 in Appendix B for completeness.

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)

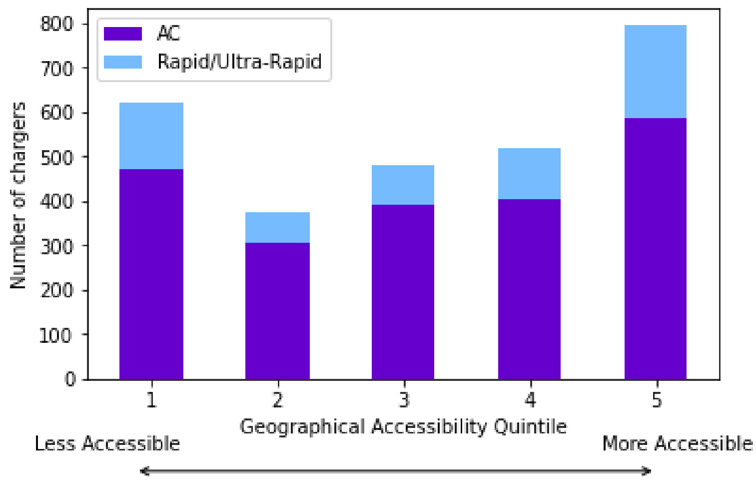

Figure 4.7: The absolute number of EV chargers on the ChargePlace Scotland public network found in each Geographical Accessibility Index quintile, where a lower quintile generally indicates a less accessible area, and a higher quintile generally indicates a more accessible area

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 [25, 29] mentioned in Section 1.2, 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 (for example, Scotland has been identified to have an income inequality greater than the average for our European counterparts [191, 192]. Diverse population structures also exist in Scotland, with many rural and island communities. Circa 17% of Scotland's population live in accessible or remote rural areas, and accessible rural areas saw a more significant population growth across

2011 to 2021 than urban areas [193]. Island communities have also seen an overall population growth, with the growth most significant in the islands better connected to the mainland such as Orkney [194]) 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 [195]. 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 3,059 square kilometres [195] 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. It is important to note that, as mentioned in Section 1.3, there are approximately 6,000 public chargers in Scotland, with ChargePlace Scotland hosting just under 3,000 of these chargers [45]. This highlights that other charging networks are playing an increasingly important role in the expansion of the overall charging network in Scotland.

Therefore, in relation to sub-question a) (concerning where public EV chargers are currently located), the 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.

4.3.3 Public Electric Vehicle 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 4.8 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.

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.

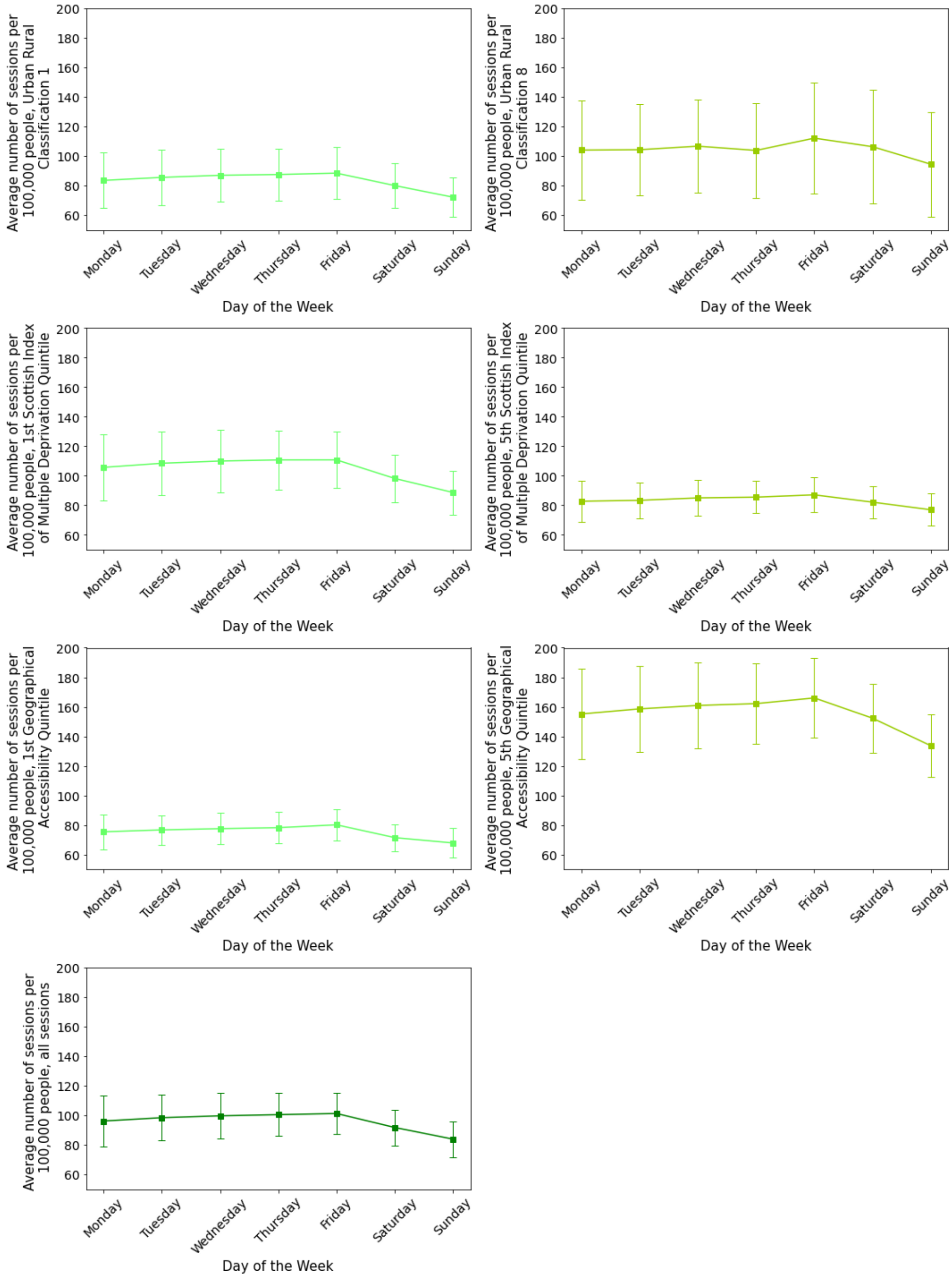

Figure 4.8: The average number of sessions taking place each day of the week on all chargers (AC and rapid) on the ChargePlace Scotland public EV charging network for all areas and for Urban Rural Classification 1 and 8 areas and first and fifth quintiles of the Scottish Index of Multiple Deprivation and Geographical Accessibility Index areas

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 2.5, most journeys tend to occur on a Friday, according to the Scottish Household Survey [145]. 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 [125, 126].

Figure 4.9 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. As shown, 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., as expected. These trends in session start time tend to align with times of peak energy demand in the UK [196], with 84.4% of sessions taking place between 8 a.m. and 9 p.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.

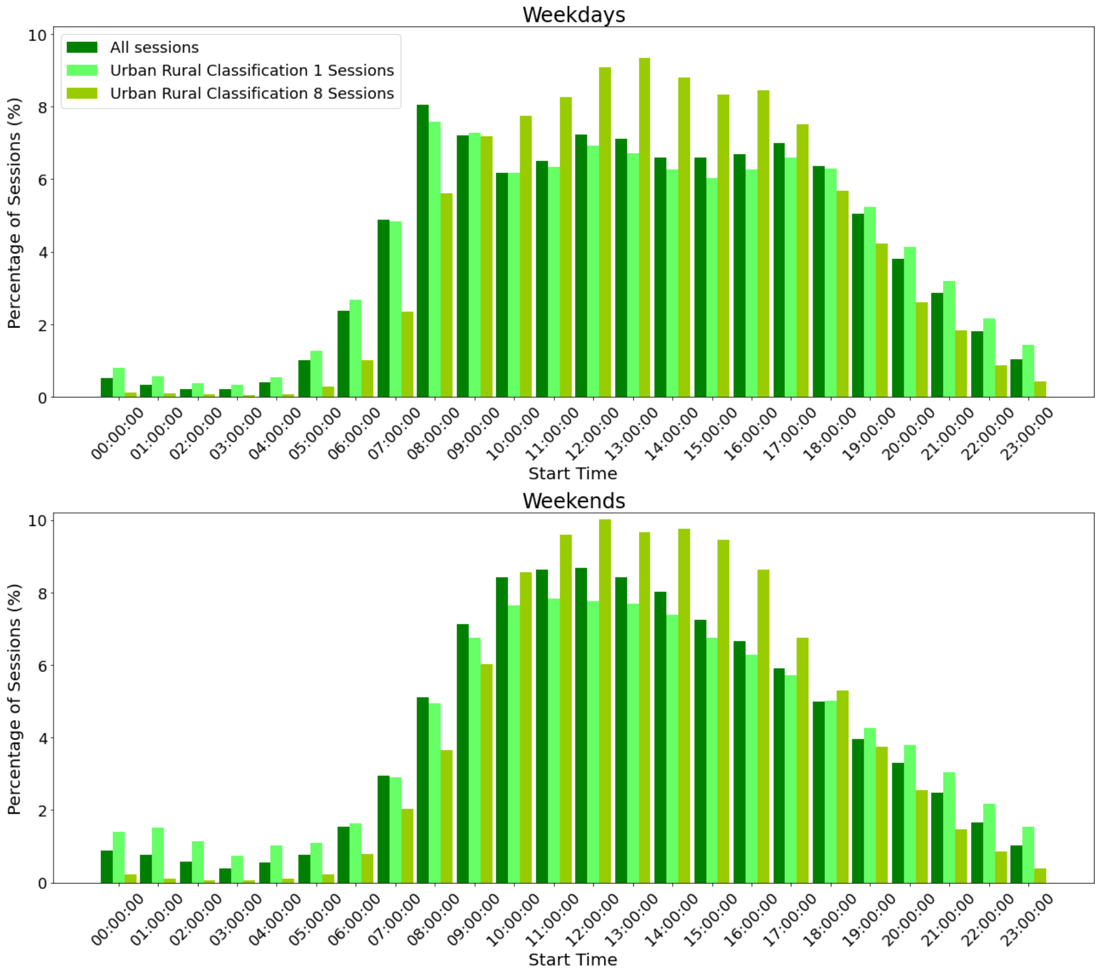

Figure 4.9: Trends in start time of charging sessions on the ChargePlace Scotland public EV charging network for all sessions, and sessions in Urban Rural Classifications 1 and 8. Chargers of both charging speeds (AC and rapid) are included

As illustrated by Figure 4.9, 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. Key groups who may use public charging overnight include people who tend to work night shifts and have unusual patterns, or those who have public chargers near their place of residence and otherwise do not have access to residential charging. 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 4.10 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 4.11 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 2.5, 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.

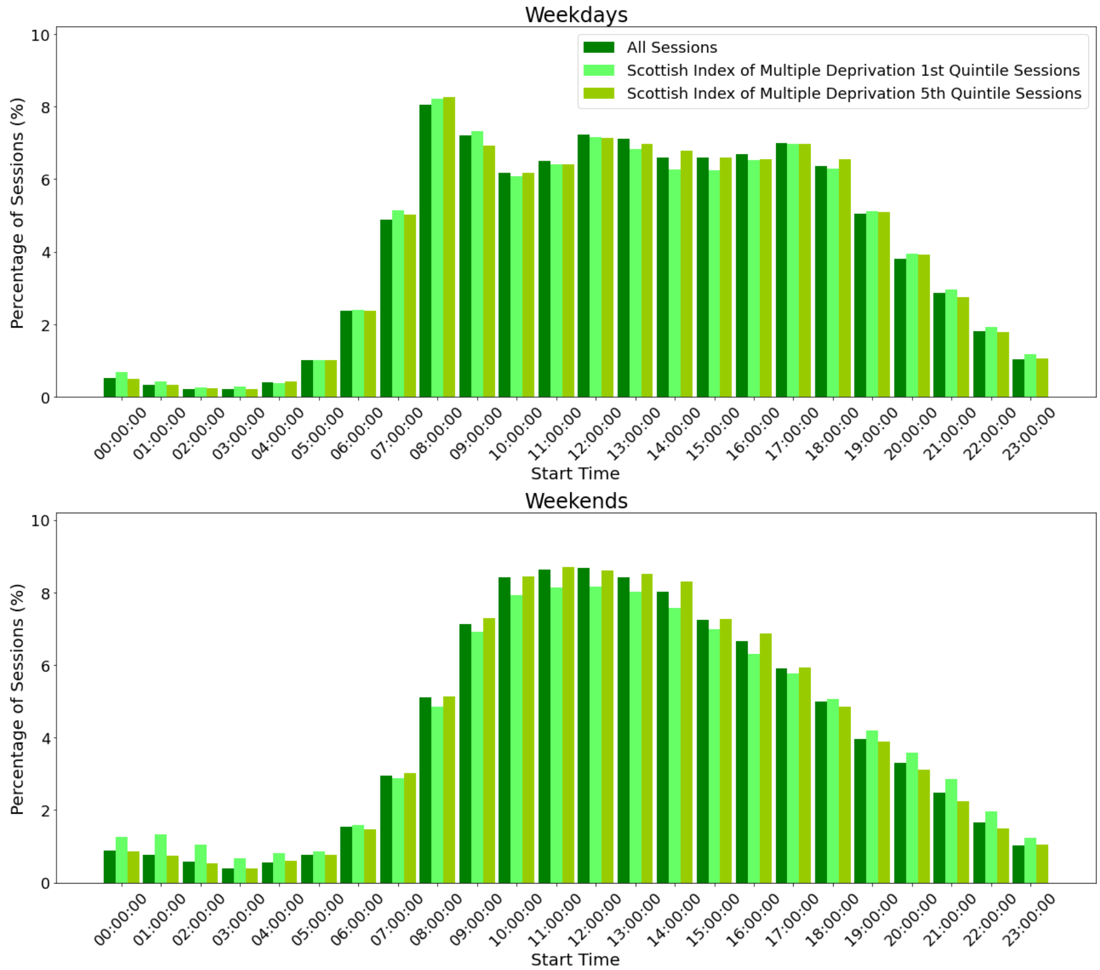

Figure 4.10: Trends in start time of charging sessions on the ChargePlace Scotland public EV charging network for all sessions, and sessions in first and fifth Scottish Index of Multiple Deprivation quintiles. Chargers of both charging speeds (AC and rapid) are included

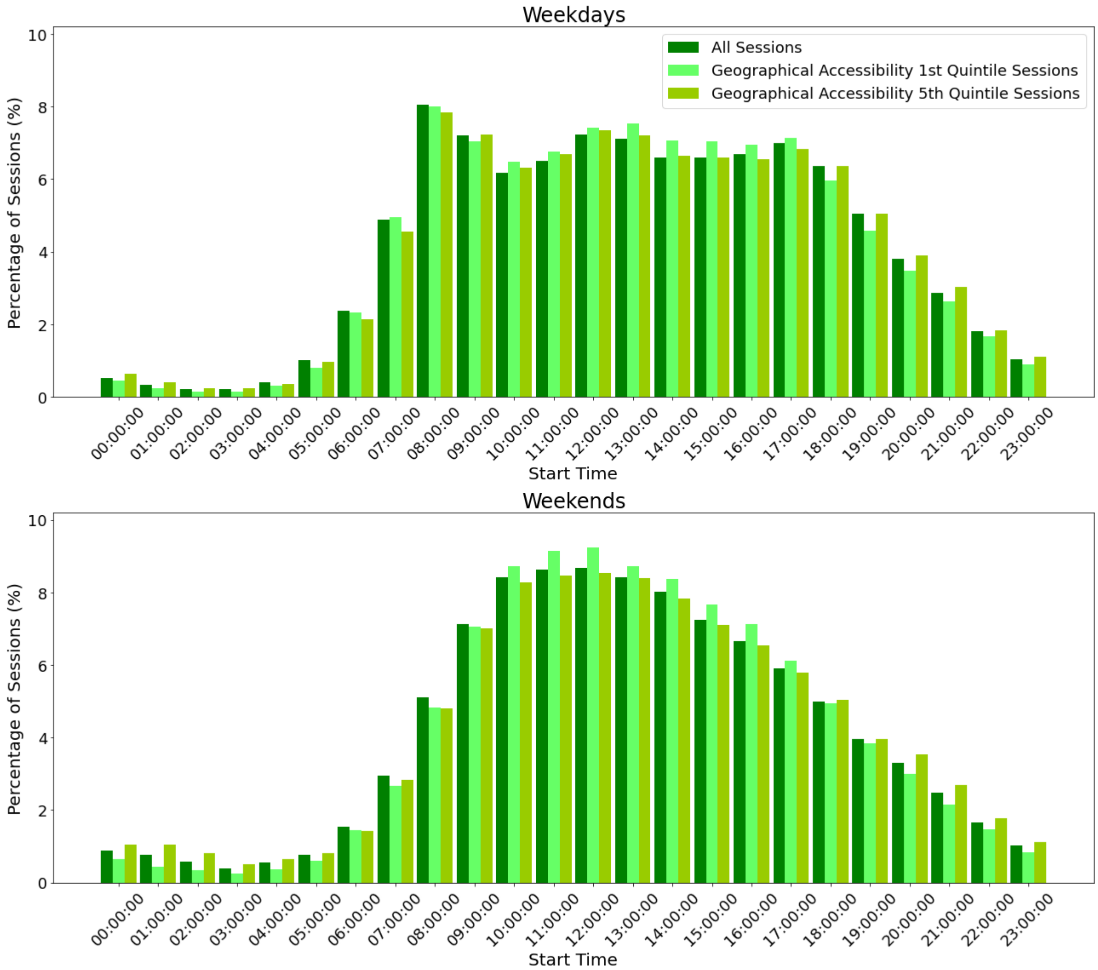

Figure 4.11: Trends in start time of charging sessions on the ChargePlace Scotland public EV charging network for all sessions, and sessions in first and fifth Geographical Accessibility Index quintiles. Chargers of both charging speeds (AC and rapid) are included

As mentioned in Section 2.3, 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 2.4) were considered. Figure 4.12 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.

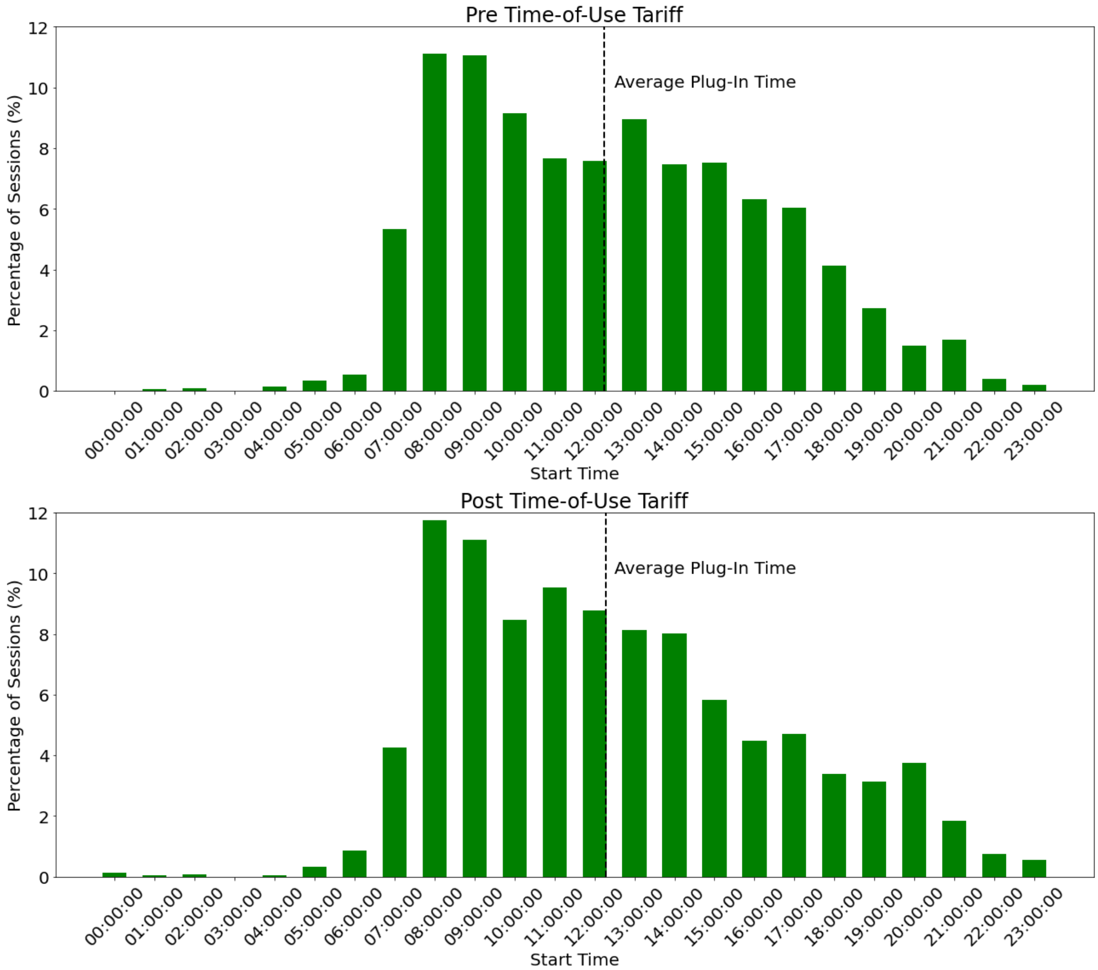

Figure 4.12: Trends in start time of charging sessions for nine chargers in East Lothian on the ChargePlace Scotland public EV charging network before and after introduction of a time-of-use tariff, with the average plug-in time marked by a vertical black dotted line

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 4.2.2. 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. The relatively modest shift in time-of-use may be because the use of public chargers is more driven by the need to charge than changes in cost. Time-of-use tariffs may be more effective for residential charging as the charger is always readily available when the car and user are at home. Public charging on the other hand, often requires the user to travel to access a charger or to make use of charging en-route.

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 (2,907 charging sessions) to consider before the time-of-use tariff introduction and one year of data (5,903 charging sessions) to consider after the time-of-use tariff's introduction.

Therefore, in relation to sub-question b) (concerning when public EV chargers tend to be used), 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.

4.3.4 Impact of Public Electric Vehicle Charging Tariffs on Utilisation

As described in Section 2.4, twelve local authorities introduced tariffs during the dataset time period. Table 4.3 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 4.3, 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 4.3, 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 4.13, 4.14 and 4.15 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 4.3.

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 [148].

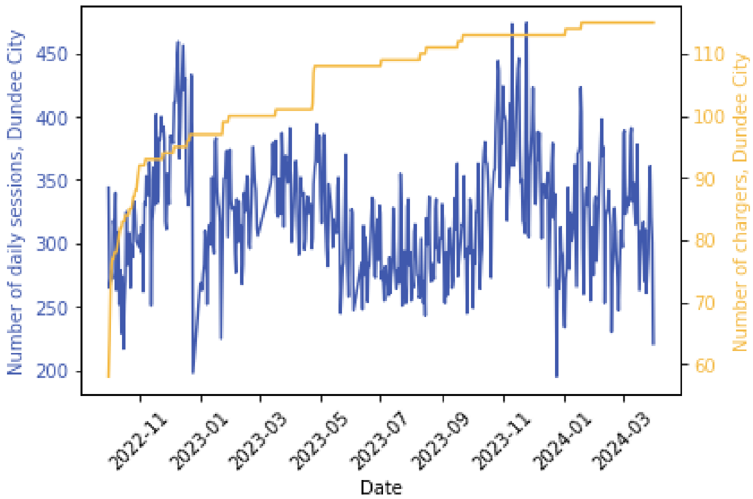

Figure 4.13: The number of sessions taking place in Dundee City (on chargers of both speeds, AC and rapid), along with the number of chargers observed. Dundee City already had a tariff in place during this time period

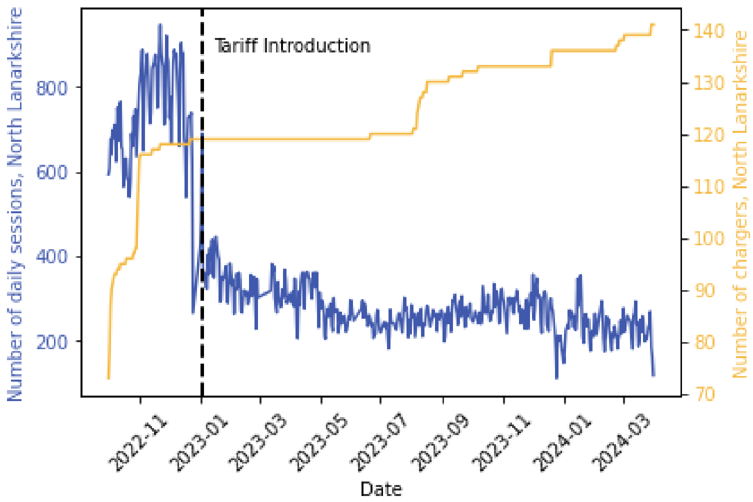

Figure 4.14: The number of sessions taking place in North Lanarkshire (on chargers of both speeds, AC and rapid), along with the number of chargers observed. North Lanarkshire introduced a tariff on 4 January 2023, illustrated by the vertical black dotted line

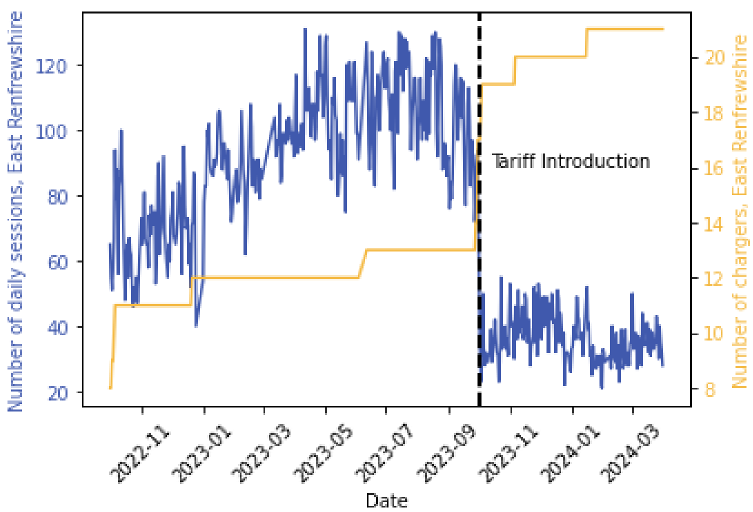

Figure 4.15: The number of sessions taking place in East Renfrewshire (on chargers of both speeds, AC and rapid), with the number of chargers observed. East Renfrewshire introduced a tariff on 1 October 2023, illustrated by the vertical black dotted line

It is also pertinent to consider the possible impacts of tariff introductions on neighbouring free chargers. Figures 4.16, 4.17 and 4.18 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.

Figures 4.16, 4.17 and 4.18 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 1.2, most EV drivers currently have access to residential charging [24]. Therefore, it is possible that a different effect may be observed as EV adoption reaches further into markets of consumers without home charging capabilities.

Table 4.3: 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 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) [197]	242.2	54.0	-77.7	5369.1	1261.9	-76.5
Continued on next page...						

Local Authority (Tariff Introduced)	Average 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 (%)
East Dunbartonshire (2 October 2023) [198]	85.4	38.6	-54.8	1999.3	895.8	-55.2
East Renfrewshire (1 October 2023) [199]	96.1	37.6	-60.9	2380.7	903.8	-62.0

Continued on next page...

Local Authority (Tariff Introduced)	**Average 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) [200]	108.4	49.5	-54.3	2390.0	963.7	-59.7
North Lanarkshire (4 January 2024) [201]	216.9	78.8	-63.7	4851.8	1699.8	-65.0
Continued on next page...						

Local Authority (Tariff Introduced)	**Average 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 (%)**
Perth and Kinross (1 January 2023) [202]	256.1	125.7	-50.9	5260.8	2426.0	-53.9
Renfrewshire (1 April 2023) [203]	198.0	95.0	-52.0	4010.3	1831.9	-54.3

Continued on next page...

Local Authority (Tariff Introduced)	**Average 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 (%)**
Shetland Islands (11 April 2023) [204]	193.0	74.4	-61.4	3232.9	1519.4	-53.0
South Lanarkshire (1 November 2022) [205]	90.0	70.0	-22.2	1894.6	1586.9	-16.2

Continued on next page...

Local Authority (Tariff Introduced)	**Average 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 (%)**
Stirling (1 February 2023) [206]	481.6	276.5	-42.6	10074.1	5692.9	-43.5
West Dunbartonshire (1 June 2023) [207]	90.1	72.6	-19.5	1542.7	1512.9	-1.9

Continued on next page...

Local Authority (Tariff Introduced)	**Average 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 (%)**
West Lothian (1 February 2023) [208]	159.5	71.8	-55.0	3412.9	1397.2	-59.1

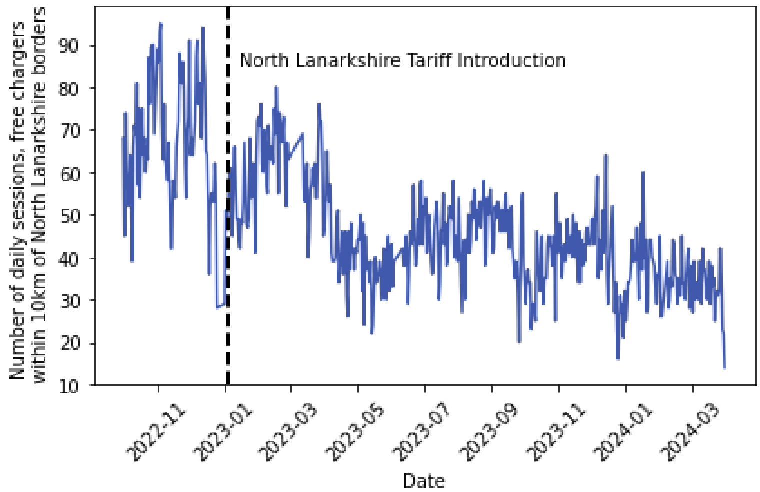

Figure 4.16: The number of sessions taking place on chargers within 10 km of North Lanarkshire borders that were free to use at the time of charging tariff introduction for North Lanarkshire council-owned chargers (the date of tariff introduction is represented by the vertical black dotted line

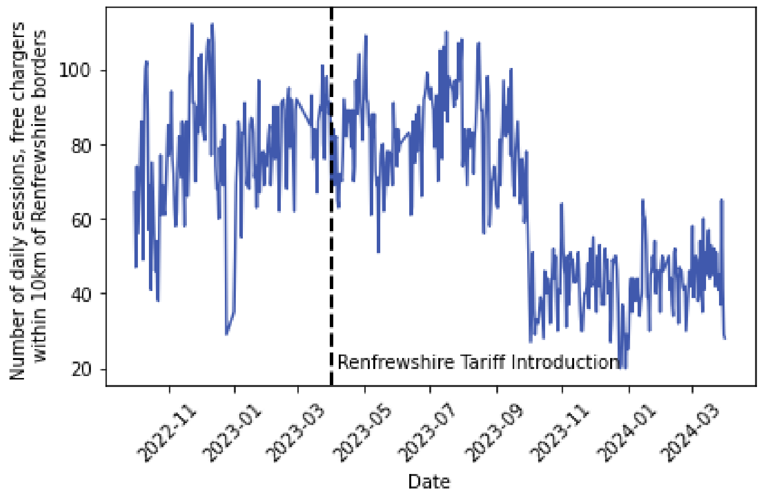

Figure 4.17: The number of sessions taking place on chargers within 10 km of Renfrewshire borders that were free to use at the time of charging tariff introduction for Renfrewshire council-owned chargers (the date of tariff introduction is represented by the vertical black dotted line)

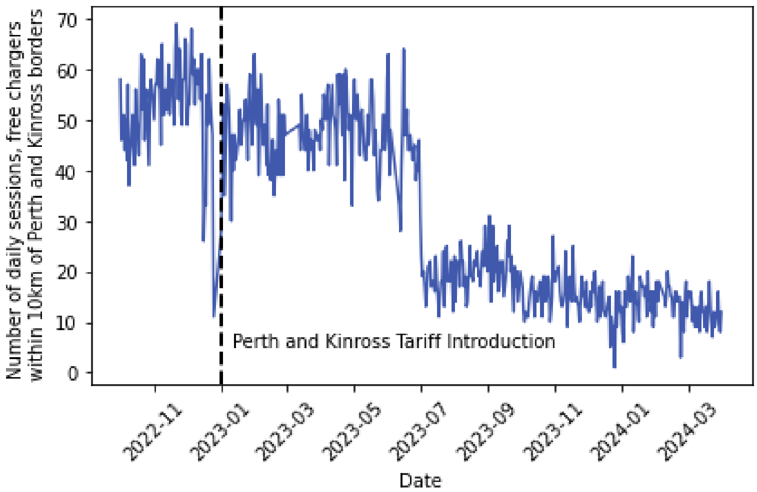

Figure 4.18: The number of sessions taking place on chargers within 10 km of Perth and Kinross borders that were free to use at the time of charging tariff introduction for Perth and Kinross council-owned chargers (the date of tariff introduction is represented by the vertical black dotted line)

In relation to sub-question c) (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. This indicates that the drop in demand for public chargers after tariff introduction is likely being otherwise met via residential chargers.

4.3.5 Characteristics of the Most Used Chargers

The average number of daily sessions experienced by chargers in the dataset ranges from 0 to 5.3 sessions for AC chargers and from 0 to 12.9 sessions for rapid/ultra-rapid chargers. As shown in Figure 4.19, 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.

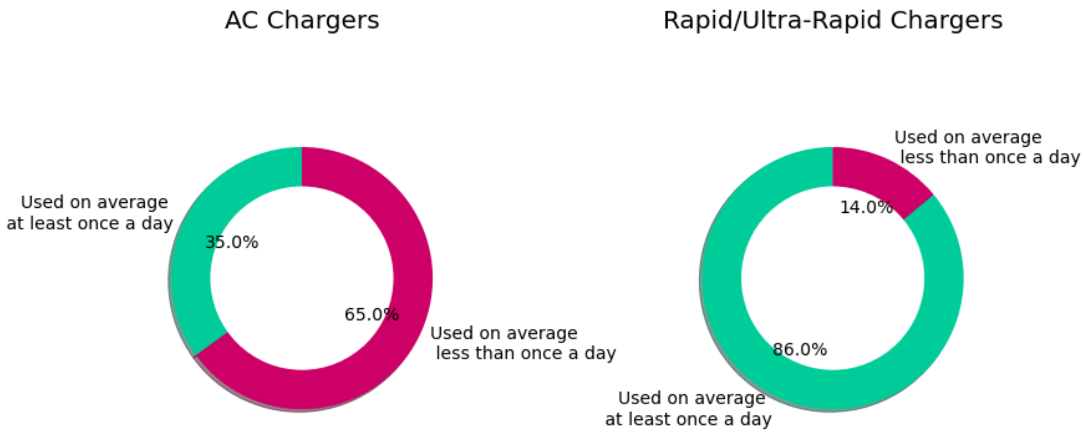

Figure 4.19: In total, 35% of AC chargers (left) experience at least one daily session, while 86% of rapid/ultra-rapid chargers (right) experience at least one daily session

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 4.20, 4.21 and 4.22 show that the most utilised AC chargers are mainly in urban, geographically accessible areas with low levels of deprivation.

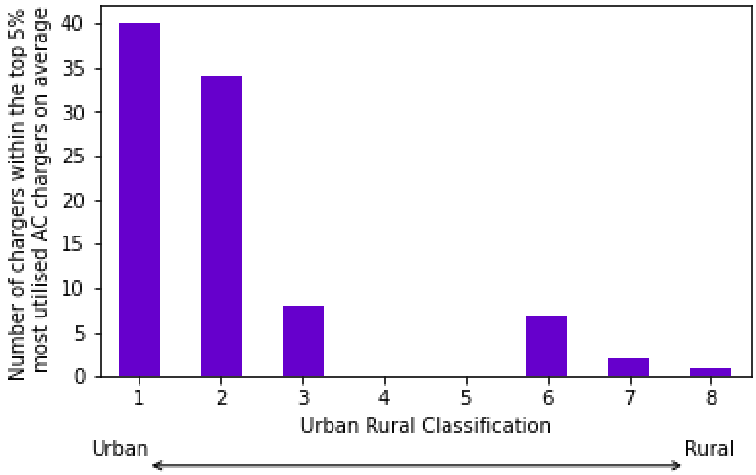

Figure 4.20: The number of chargers per Urban Rural Classification that are within the top 5% most utilised AC chargers by average daily sessions

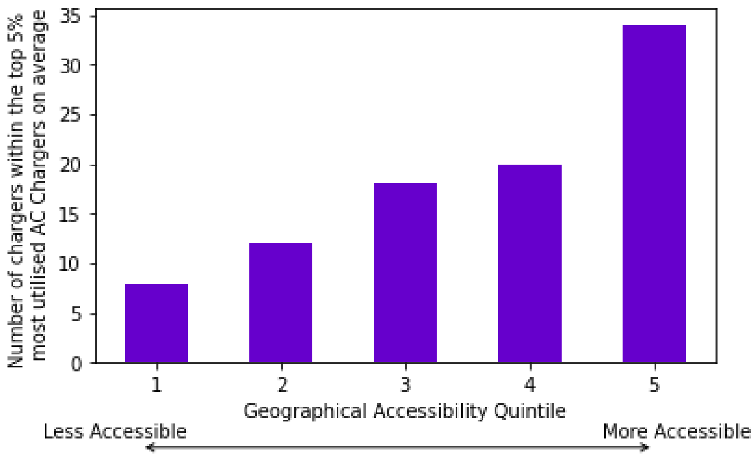

Figure 4.21: The number of chargers per Geographical Accessibility Index quintile that are within the top 5% most utilised AC chargers by average daily sessions

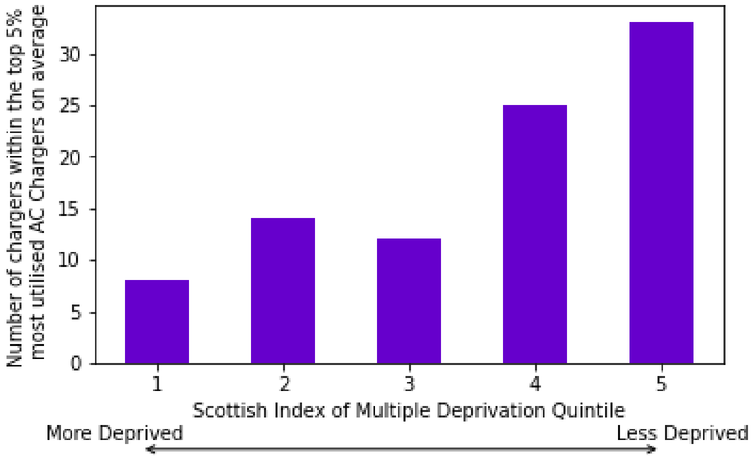

Figure 4.22: The number of chargers per Scottish Index of Multiple Deprivation quintile that are within the top 5% most utilised AC chargers by average daily sessions

As demonstrated by Figure 4.20, 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 4.21 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 4.22 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 1.2, a chicken-versus-egg feedback effect can exist between the presence of public EV chargers and local EV adoption [30–32]. 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 2.5, 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.

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 4.23, 4.24 and 4.25 show that the most utilised rapid chargers are mainly in urban, geographically accessible areas with high levels of deprivation.

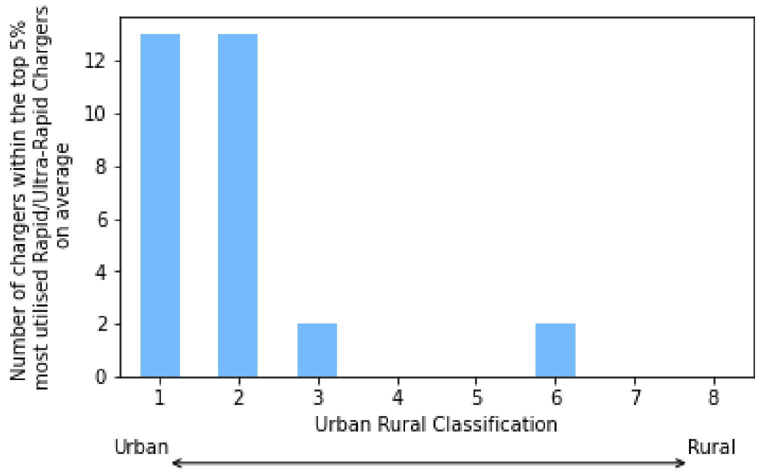

Figure 4.23: The number of chargers per Urban Rural Classification that are within the top 5% most utilised rapid chargers by average daily sessions

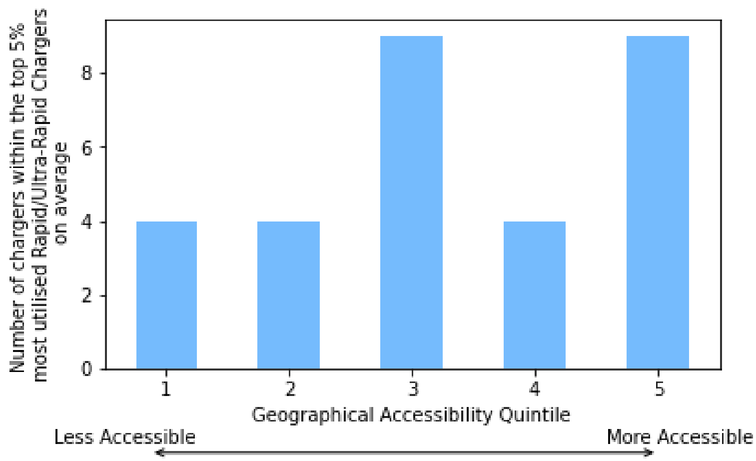

Figure 4.24: The number of chargers per Geographical Accessibility Index quintile that are within the top 5% most utilised rapid chargers by average daily sessions

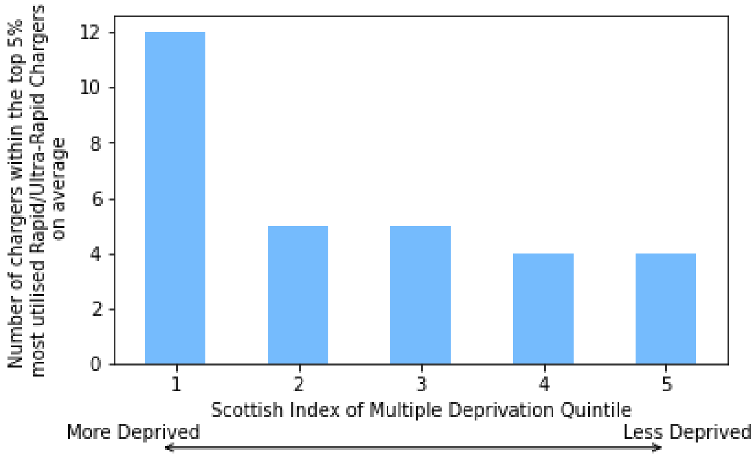

Figure 4.25: The number of chargers per Scottish Index of Multiple Deprivation quintile that are within the top 5% most utilised rapid chargers by average daily sessions

As shown in Figure 4.23, only 2 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 4.24 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 9 chargers. The first, second, and fourth quintiles all had 4 chargers each. Figure 4.25 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 5 chargers, while the fourth and fifth quintiles both had 4 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 [141]. 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.

Figure 4.26 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

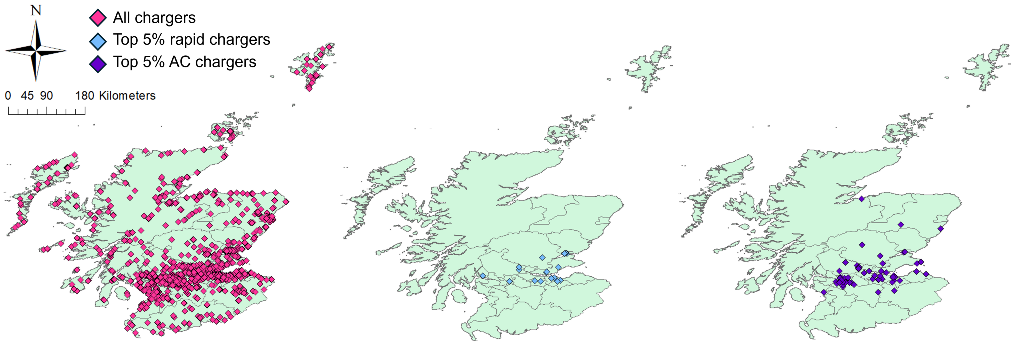

Figure 4.26: Positions of all chargers in the dataset (left), the top 5% most utilised rapid chargers by their average daily sessions (middle), and the top 5% most utilised AC chargers by their average daily sessions (right), including thematic layer representing local authority boundaries [48]

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.

In relation to sub-question d) (concerning the characteristics associated with the most utilised chargers), 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.

4.3.6 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 [196], 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.

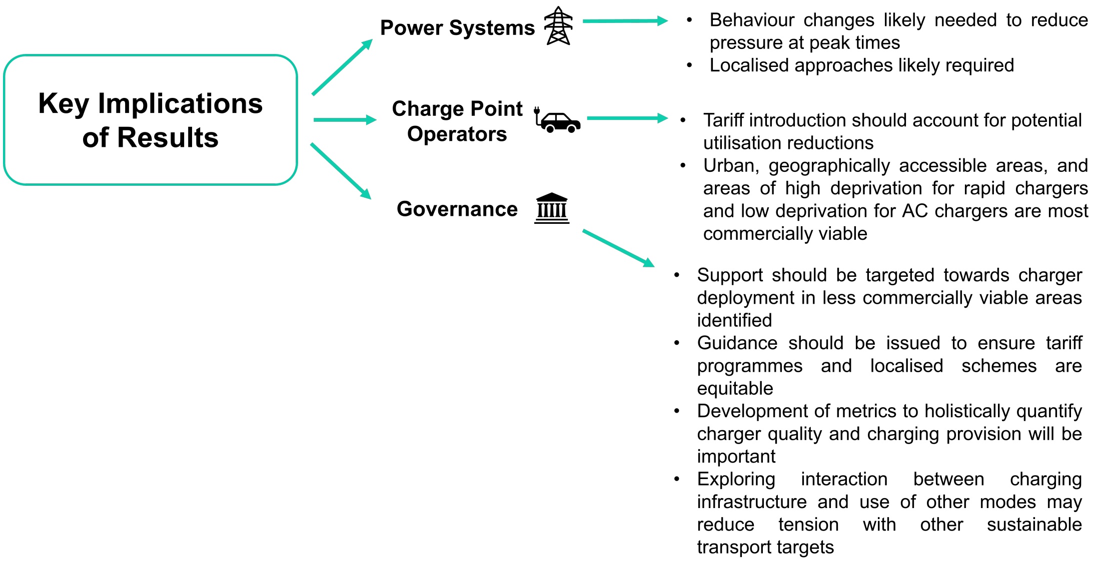

Figure 4.27: Summary of the key implications the results of this chapter have for policy and transport planning for three key stakeholders - power systems, charge point operators, and governance

4.4 Implications for Policy, Practice and Future Work

The results of this chapter 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 4.27. It is important to bear in mind the limitations of the research methodology, outlined in detail in Section 4.2.3. 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.

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 4.3.4, 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 [38, 39] (see Section 1.2) 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 1.3) 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 1.2) surrounding EV adoption [30–32]. 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 4.3.2), 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 [46].

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 4.3.3). However, the possibility that rural EV drivers may have to drive further to access chargers, also touched on in Section 4.3.3, 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 4.3.4. 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 [11]. 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 [209].

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 2.5, given that 55.2% of trips are made by car in Scotland (with this rising to 69% specifically in the most rural areas) [145], 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.

4.5 Conclusions

This chapter has developed and analysed a dataset of EV charging sessions taking place on the ChargePlace Scotland network, spanning a total of 2,786 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 (mentioned in Section 1.3), makes it pertinent to obtain insights into how the network can be developed effectively and equitably. This chapter 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).

Therefore, in relation to Research Question 2 (as described in Chapter 1), the results of this chapter have provided the following insights into the current state of Scotland's public charging network: 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.

Additionally, based on these findings, the following insights pertaining to policy and practice to support an equitable transition 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.

Furthermore, in terms of developing inclusive public charging provision in the Scottish context, it is important to understand the charger population required that will enable equitable geographic access to chargers. Although the Scottish Government have adopted the Climate Change Committee's car kilometre based recommendation to install a further 24,000 chargers by 2030, it is unclear if this charger population will achieve an inclusive spatial arrangement of chargers that will allow the population across Scotland equitable access to public EV charging facilities. Therefore, it is important to investigate the charger population required by 2030 in Scotland through approaches that do and do not account for population dispersion to understand both future public charging requirements and the impact that population dispersion has on this. This will be the focus of Chapter 5.

Chapter 5

Equitable Scottish Public Electric Vehicle Charging - 2030 Requirements

5.1 Introduction

As discussed in Chapters 1 and 2, the Scottish Government has adopted the Climate Change Committee's car and van kilometre based recommendation to supplement Scotland's existing 6,000 public EV chargers by installing an additional 24,000 chargers by 2030. Chapters 3 and 4 explored the critical nature of developing public charging infrastructure to enable an equitable transition to EVs that in turn will support achievement of key governmental emission reduction targets. Alongside pledging to the installation of the targeted population of chargers, the Scottish Government has also highlighted their commitment to develop a public network that is equitably accessible to all [26]. The results of Chapter 4 showed that, while the ChargePlace Scotland network provided relatively good coverage of socially deprived areas, there were disparities in provision across urban and rural areas where the absolute number of chargers was more concentrated in urban areas but the number of chargers per 100,000 was more concentrated in rural areas. As also discussed in Chapter 1, the use of a car kilometre based approach for quantifying public charging demand assumes that all activity takes place at a single central point and may lead to some communities being left behind as the distribution of people and places is not considered. The impact of population dispersion on public charging requirements in the Scottish context is unclear and there is a risk that overly simple modelling leads to estimation of fewer chargers required. This highlights the need to understand the impact that population distribution may have on projections for charger population requirements to support equitable geographic access to chargers in Scotland.

The current chapter, therefore, aims to evaluate the number of chargers required in Scotland in 2030 under different scenarios for charging technology adoption, and in the context of future scenarios found to achieve emissions targets in Chapter 3. To evaluate and quantify impacts from population dispersion, two different techniques will be applied to assess the required charger population in each scenario: a geospatially-agnostic approach which utilises projected EV kilometres travelled (Chapter 3) and average charge duration and energy consumption data (Chapter 4); and a geospatially-driven GIS approach which additionally accounts for population dispersion to quantify the public charger population required to enable equitable geographic access, as well as the gap-risk of a non-spatial assessment. As shown in Chapter 3, the scenarios which met the government emissions reduction target were 'A+B+D', 'B+C+D' and 'A+B+C+D' and the scenarios which met the car kilometre reduction target were 'B + D', 'B + C + D', 'A + B', 'A + B + C', 'A + B + D' and 'A + B + C + D' (where 'A' is a modal shift from car to active travel, 'B' is a modal shift from car to bus, 'C' is electrification of buses and 'D' is the transition to EVs). Since, the electrification of buses does not impact car kilometres travelled or EV adoption, and since buses would use their own private charging network, scenario component 'C' does not influence public EV charging requirements. 'C' is therefore removed in the current analysis, leaving the following sustainable intervention adoption scenarios to be considered in this chapter: 'A+B+D' (active travel, car to bus and EV transition), 'B+D' (car to bus and EV transition) and 'A+B' (active travel and car to bus). Further details of the sustainable intervention adoption scenarios are given in Table 3.4. In addition, three charging-technology-adoption scenarios will be considered: a network where all chargers are AC, a network where all chargers are rapid, and a network where there is a 50/50 split of AC and rapid charging technologies. The overall elements of Chapters 3 and 4 that feed into the analysis of the current chapter are summarised in Figure 5.1.

This chapter therefore addresses Research Question 3, as outlined in Chapter 1 – *What scale of EV charger deployment is required by 2030 to ensure equitable geographic access to Scotland's public EV charging network?* Additionally, the following supporting sub-questions are explored:

a) What is the impact of population distribution on the charger population required by 2030 in Scotland?

b) How does charger technology impact the number of chargers required by 2030 in Scotland, and the necessary share of AC versus rapid charging technology?

The remainder of this chapter is structured as follows: Section 5.2 presents the applied methodology, detailing both the geospatially-agnostic and geospatially-driven approaches; Section 5.3 presents, analyses and discusses the results; Section 5.4 explores the implications the results have for policy and practice; and Section 5.4 concludes the chapter.

5.2 Methodology

As outlined in Section 5.1, the research methodology is comprised of two separate parts aiming to quantify the public EV charger population required by 2030 in Scotland. The methodology of both approaches – the geospatially-agnostic approach based on EV kilometres travelled and the geospatially-driven approach incorporating GIS to account for population dispersion – will be outlined in the following subsections. Subsequently, the necessary share of AC versus rapid chargers required to make up the Scottish Government's targeted 30,000 chargers is determined, while again accounting for impacts of

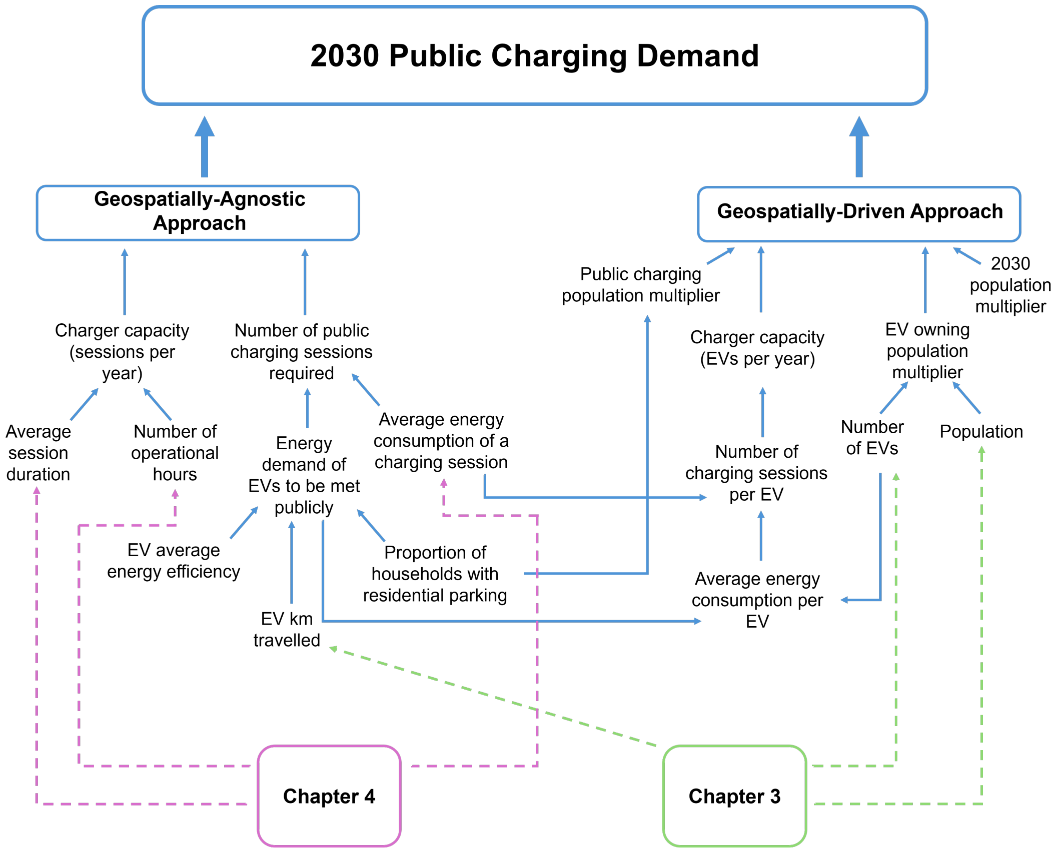

Figure 5.1: Flowchart representing the workflow of Chapter 5 including all key parameters and an indication of how previous chapters feed in

population dispersion. Figure 5.1 provides an overview of the parameters involved in the analyses and an indication of where the work of previous chapters feeds into the current workflow.

5.2.1 Geospatially-Agnostic Approach

As mentioned in Section 5.1, outputs for projected EV kilometres travelled in 2030 from Chapter 3 and average charge duration and energy consumption data from the dataset developed in Chapter 4 are used for this analysis. Using this data as inputs, the number of public charging sessions required to meet the energy demand from EVs in 2030 may be found. Then, charger capacity in terms of the number of charging sessions a charger can accommodate in one year is determined. Combining these, the *geospatially-agnostic* number of public chargers required in 2030 may be estimated. These various steps are detailed below.

Public Charging Sessions Required: The total energy consumed by EVs in Scotland in 2030 (E) is found using the projected EV kilometres travelled (D) and the average energy efficiency of an EV (α) as follows:

$$E = D\alpha \tag{5.1}$$

A value of α = 0.189 kWh/km [75] was assumed. The system dynamics projected EV kilometres travelled (Chapter 3) vary for each sustainable intervention adoption scenario, outlined in Table 5.1.

Table 5.1: Projections for electric vehicle kilometres in Scotland by 2030 from Chapter 3

Scenario	EV kilometres travelled (D), Scotland 2030 (million km)
'A+B+D' (active travel, car to bus and EV transition)	11,895.784
'B+D' (car to bus and EV transition)	15,595.856
'A+B' (active travel and car to bus)	4,554.842

Next, the proportion of this energy that must be met publicly (E_P) is found. As mentioned in Chapter 2, 44% of Scottish households do not have access to private residential parking [149]. Assuming that all households with private residential parking install a home charger and meet their entire charging requirements residentially, then the proportion of EVs using the public charging network (ρ) is 0.44. Therefore:

$$E_P = E\rho \tag{5.2}$$

The total number of public charging sessions required (S) is then calculated based on the average energy consumed in a public charging session (η) which is 21 kWh (from developed dataset in Chapter 4, including data for both AC and rapid chargers):

$$S = \frac{E_P}{\eta} \tag{5.3}$$

Charger Capacity (Charging Sessions per Year): The number of sessions a charger can accommodate per year depends on the charger speed. From the dataset developed in Chapter 4, the average duration of a session taking place on an AC charger (d_{AC}) is 248.585 minutes and the average duration of a session taking place on a rapid charger (d_R) is 46.162 minutes. Assuming that no sessions take place after 11 p.m. and before 6 a.m. (since the dataset developed in Chapter 4 indicated that less than 5% of sessions occurred during these hours on both weekdays and weekends), and that therefore there are 17 operational charging hours which equates to 1020 operational minutes in a day, the maximum number of sessions a rapid (M_R) and AC (M_{AC}) charger can accommodate per year can then be calculated:

$$M_R = 365 \times \frac{1020}{d_R} \tag{5.4}$$

$$M_{AC} = 365 \times \frac{1020}{d_{AC}} \tag{5.5}$$

Public Chargers Required: The number of chargers required (N_{AC} for AC chargers and N_R for rapid chargers) can then be expressed in terms of the respective charger capacities and the total number of sessions required:

$$M_R N_R + M_{AC} N_{AC} = S \tag{5.6}$$

Finding the number of chargers required in the charging technology adoption scenario where all chargers are AC involves setting N_R to zero and solving for N_{AC}, while finding the number of chargers required in the charging technology adoption scenario where all chargers are rapid involves setting N_{AC} to zero and solving for N_R. To find the total number of chargers in the scenario where there is a 50/50 split of AC and rapid chargers, a rapid to AC conversion factor (γ) must be calculated:

$$\gamma = \frac{M_R}{M_{AC}} \tag{5.7}$$

The following equation can then be used to convert the 'all rapid' case to a scenario where there are a certain split of AC and rapid chargers:

$$N_{Total} = (\delta_R - X) + \gamma X \tag{5.8}$$

Where N_{Total} is the total number of chargers; δ_R is the number of chargers in the 'all rapid' case; X is the number of rapid chargers to be 'converted' to AC chargers; and γ is the rapid to AC conversion factor (Equation 5.7). In Equation 5.8, the term (δ_R–X) is equal to N_R and the term γX is equal to N_{AC}. In the scenario where there is a 50/50 split of AC and rapid chargers, $0.5N_{Total} = N_R$. Therefore, Equation 5.8 becomes $N_R = 0.5[(\delta_R – X) + \gamma X]$. Solving for X allows the number of rapid and AC chargers to be determined. These steps can be taken to determine the number of chargers under any other desired split of AC versus rapid chargers. In this analysis, a 50/50 split is chosen as a midpoint to understand the transition between the 'all rapid' and 'all AC' cases. In comparison, although data pertaining to the current split of AC versus rapid charging across the entire Scottish public charging network is not available, Chapter 4 found that 77% of ChargePlace Scotland chargers were AC, with the remaining 23% being rapid/ultra-rapid (see Section 4.3.1). Additionally, across the entire UK public charging network, 20% of chargers are reported to be rapid/ultra-rapid [210], with the remaining 80% of chargers being AC, similar split to that found in Chapter 4 for the ChargePlace Scotland network.

5.2.2 Geospatially-Driven Approach

As mentioned in Section 1.3, the geospatially-agnostic approach assumes that all activity takes place at one central location. However, in reality population is dispersed

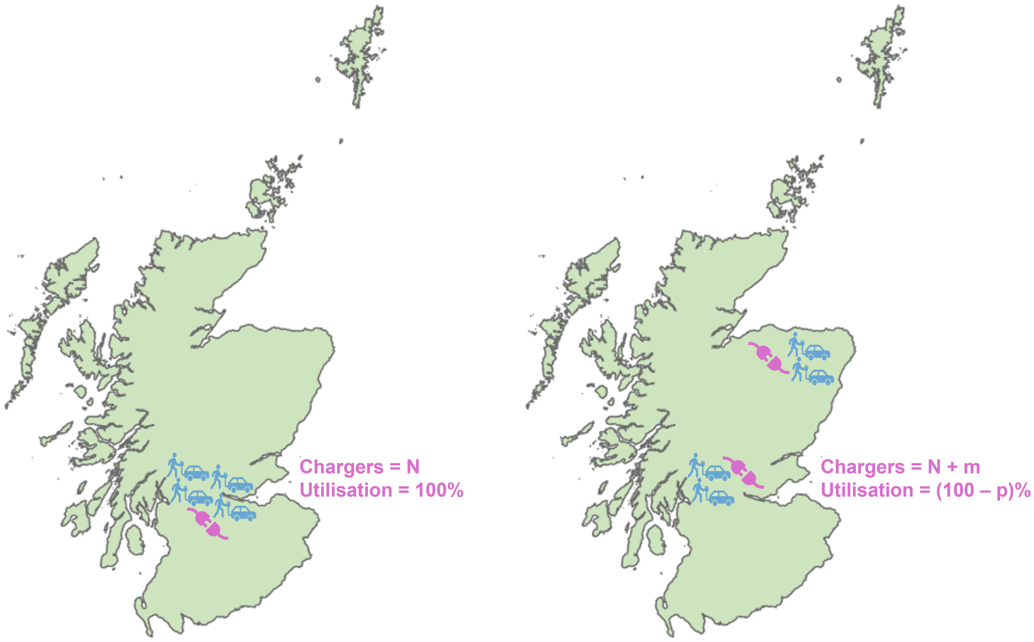

Figure 5.2: In a situation where all population is concentrated at one location (left), a minimal number of chargers (N) that are maximally utilised are required. However, in the more realistic situation where population is dispersed geographically (right), to ensure equitable geographic access, a greater charger population is required ($N + m$, where m is an additional number of chargers) although these chargers experience a lower level of utilisation ($(100 - p)\%$ where p represents a drop in utilisation)

across the land area of the country. This means that, if ensuring equitable geographic access to chargers, a greater number of chargers will be required. Distance limitations on the total population within range of any individual charger necessarily implies that, when ensuring equitable access, the utilisation of some chargers must fall below 100% in this scenario. This effect is depicted in Figure 5.2. The geospatially-driven approach undertaken in this work utilises ArcGIS Pro version 3.4.0 [211] to account for the dispersion of the population across Scotland and understand the charger population required to achieve equitable geographic access to chargers.

Firstly, a hexagonal grid pattern covering the geographical extent of Scotland was created (using the Generate Tessellation tool). Next, the population within each hexagonal cell was determined (using the Tabulate Intersection and Summary Statistics tools and population data from the Scottish 2022 census [212]). The overall analysis was con-

Figure 5.3: Maps of the 2022 Scottish census population data [212] (left), the population within 5km wide hexagonal grids (middle) and the population within 10km wide hexagonal grids (right)

ducted twice, once with the hexagons of the grid being 5km in diameter and once with the hexagons being 10km in diameter. The total number of hexagonal cells in the 5km grid was 5,927 cells, and the total number of cells in the 10km grid was 1,659 cells. Figure 5.3 shows the original census population data [212] and the populations within the 5km and 10km hexagonal grids.

The area of the grid cells acts as the service area of chargers and the width of the hexagonal cells is the maximum distance any individual within the hexagon must travel to reach a charger, as illustrated by Figure 5.4. For example, a grid cell diameter or hexagon width of 5km means that the maximum distance any individual within the hexagon must travel is 5km. Assuming an average driving speed of 30 miles-per-hour it would take a maximum of 6.2 minutes to reach a charger in the 5km hexagonal grid. This time would be 12.4 minutes for the 10km grid. The number of chargers required to service each hexagonal cell will be calculated to meet the requirements of the population.

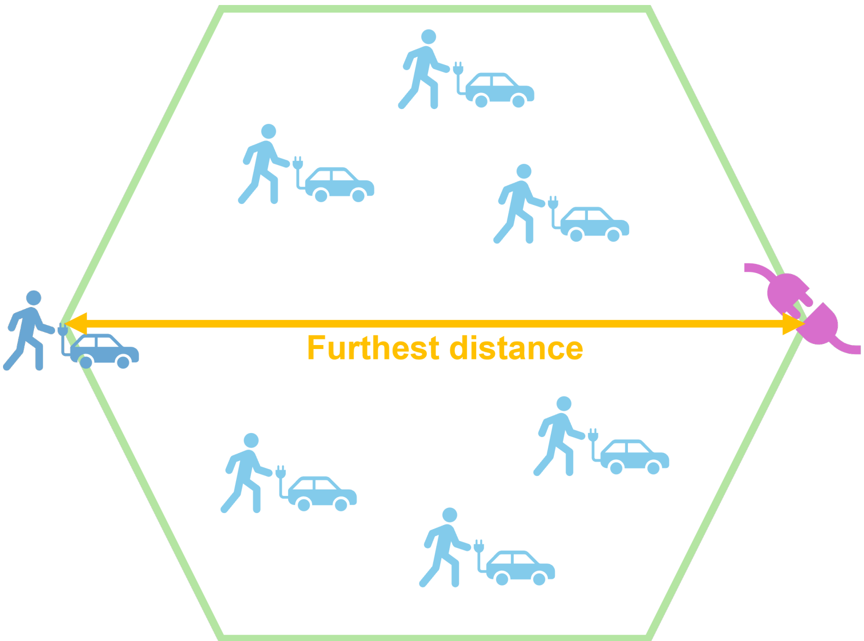

Figure 5.4: The maximum distance any individual within the hexagon would have to travel to access a charger is the width of the hexagon, in the scenario where the charger and individual are situated the maximum possible distance apart at opposite vertices

To find the number of chargers required in each cell, the following multipliers are applied to the population within each cell: a 2030 population multiplier to scale the 2022 population; an EV owning multiplier based on projections of EV penetration to find the number of EVs; and a public charging multiplier to find the number of EVs relying on the public charging network. These multipliers are detailed below. The charger capacity in terms of the number of EVs a charger can accommodate per year is also determined to find the number of chargers required in each hexagonal cell, which is then totalled to give the national charger population required. As mentioned in Section 5.1, outputs for the projected population and number of EVs in 2030 from Chapter 3 and average charging session energy consumption data from the developed dataset in Chapter 4 are used. The calculations of the population multipliers applied to calculate the number of chargers required in each cell are outlined below.

2030 Population Multiplier: The multiplier applied to scale the population from the 2022 census to the population in 2030 (P_{Scaled}) is:

$$P_{Scaled} = \frac{P_{2030}}{P_{2022}} \tag{5.9}$$

Where P_{2030} is the population in 2030 projected by the system dynamics model in Chapter 3 (5,458,714 people) and P_{2022} was the total population captured in the hexagonal cells (5,332,118 people in the 10km hexagons and 5,331,969 people in the 5km hexagons).

EV Owning Population Multiplier: Assuming that every EV has a unique owner and that no single person owns more than one EV, the EV owning population multiplier (k) can be found by:

$$k = \frac{N_{EV}}{P_{2030}} \tag{5.10}$$

Where N_{EV} is the number of EVs in 2030 projected by the system dynamics model in Chapter 3, the values for which are given in Table 5.2.

Table 5.2: Projections for the number of electric vehicles in Scotland by 2030 from Chapter 3

Scenario	**Number of EVs (N_{EV}), Scotland 2030 (vehicles)**
'A+B+D' (active travel, car to bus and EV transition)	1,933,029
'B+D' (car to bus and EV transition)	1,933,029
'A+B' (active travel and car to bus)	740,129

Public Charging Multiplier: Similar to the geospatially-agnostic approach, to find the number of EVs relying on the public charging network it is assumed that those with private residential parking install a home charger and meet their entire charging needs residentially, meanwhile those without private residential parking rely on the public network. Therefore, the public charging multiplier is $\rho = 0.44$ [149].

Chargers Capacity (EVs per Year): Again, charger capacity in terms of the number of EVs that can be accommodated by a charger in a year varies depending on charger speed. The average energy consumed by an EV in a year (E_{EV}) is calculated using the previously determined value for E in section 5.2.1:

$$E_{EV} = \frac{E}{N_{EV}} \tag{5.11}$$

The number of sessions per EV (S_{EV}) is then calculated using the average energy consumption of a charging session from Chapter 4:

$$S_{EV} = \frac{E_{EV}}{\eta} \tag{5.12}$$

The number of EVs a charger can accommodate per year is then calculated, for the all rapid (V_R), all AC (V_{AC}) and 50/50 AC/rapid ($V_{50/50}$) cases, using M_{AC} and M_R as calculated in Section 5.2.1:

$$V_{AC} = \frac{M_{AC}}{S_{EV}} \tag{5.13}$$

$$V_R = \frac{M_R}{S_{EV}} \tag{5.14}$$

$$V_{50/50} = \frac{V_{AC} + V_R}{2} \tag{5.15}$$

Chargers Required: The number of chargers required within each hexagonal cell (N_{Cell}) is then calculated for the all AC, all rapid and 50/50 AC/rapid cases respectively, where P_{Cell} is the population within each hexagonal cell:

$$N_{Cell} = \frac{P_{Cell} \times P_{Scaled} \times k \times \rho}{V_{AC}} \tag{5.16}$$

$$N_{Cell} = \frac{P_{Cell} \times P_{Scaled} \times k \times \rho}{V_R} \tag{5.17}$$

$$N_{Cell} = \frac{P_{Cell} \times P_{Scaled} \times k \times \rho}{V_{50/50}} \tag{5.18}$$

The number of chargers required within each cell is rounded up to the nearest whole number and then the total number of chargers required across all cells is calculated to find the national public charger population required. The cumulative effect of this upward round results in the additional number of chargers required and lower utilisation of some chargers compared to the geospatially-agnostic quantification, as outlined in Figure 5.2. As mentioned, accounting for population dispersion to quantify the equitably accessible charger population required means that a greater charger population will be required compared to a geospatially-agnostic quantification, although these chargers will be underutilised. Calculating the charger population required through both geospatially-agnostic and geospatially-driven approaches allows for the gap between the charger population determined through analyses that do and do not account for population dispersion to be understood.

5.2.3 Limitations

The research methodology outlined in the previous subsections has associated assumptions and limitations summarised here for clarity.

Assumptions: Firstly, average values are used for EV energy consumption, charging session energy consumption, charging session duration and the proportion of households without access to private residential parking. Additionally, it is assumed that no charging sessions take place on public chargers between 11 p.m. and 6 a.m. Analysis of the dataset developed in Chapter 4 showed that less than 5% of sessions take place between these hours both on weekdays and at weekends. However, these trends may shift as EV uptake develops. It is also assumed that those with private residential parking install a residential charger and meet all of their charging needs at home. Although it is widely reported that most EV charging occurs residentially [148, 213, 214], some drivers may not be able to meet their entire charging requirements there particularly if they tend to complete longer journeys and require charging en route.

Geospatially-driven specific limitations: The analysis accounts for the usual resident population within each hexagonal cell only. This means that impacts of tourism or regular traffic flow that mean certain areas tend to experience many shorter-term visitors (e.g. retail parks, hospitals etc.) are not considered. Additionally, it is assumed that populations within hexagonal cells meet their charging needs within their cells and that each EV has a unique owner. Population multipliers were also applied uniformly across the hexagonal grid, meaning that spatial variation of things like growth in population or EV adoption are not forecast. It is important to bear in mind that the maximum distance to travel and examples given for travel time based on the dimensions of the hexagonal grid are based on the Euclidean distance between opposite hexagon vertices. Additionally, the average speed travelled in urban, densely populated areas may be much less than the typical speed limit of 30 miles per hour. Therefore, in reality, travel times and distances to and from chargers may be longer.

5.3 Results and Discussion

In conducting the geospatially-agnostic and geospatially-driven analyses outlined in Section 5.2, the charger population required by 2030 in Scotland has been estimated under the different scenarios considered for achieving emission reduction targets (see Section 5.1). The results using the 5km hexagonal grid are presented in Figure 5.5. As shown, the number of chargers likely to be required across all the scenarios is less than the government targeted 30,000 chargers apart from the scenarios which featured the EV transition and an 'all AC' charger technology choice. Perhaps unsurprisingly, scenarios including the EV transition required more chargers than the scenario that does not feature the EV transition. The charger population required for scenario 'EV transition + car to bus + active travel' ranged from 5,841 chargers in the 'all rapid' case determined geospatially-agnostically to 35,748 chargers in the 'all AC' case determined by the geospatially-driven approach. For the scenario 'EV transition + car to bus', the charger population required ranged from 7,658 chargers in the 'all rapid' case determined geospatially-agnostically to 46,606 chargers in the 'all AC' case determined by the geospatially-driven approach. Meanwhile, the charger population required for scenario 'car to bus + active travel' ranged from 2,237 chargers in the 'all rapid' case

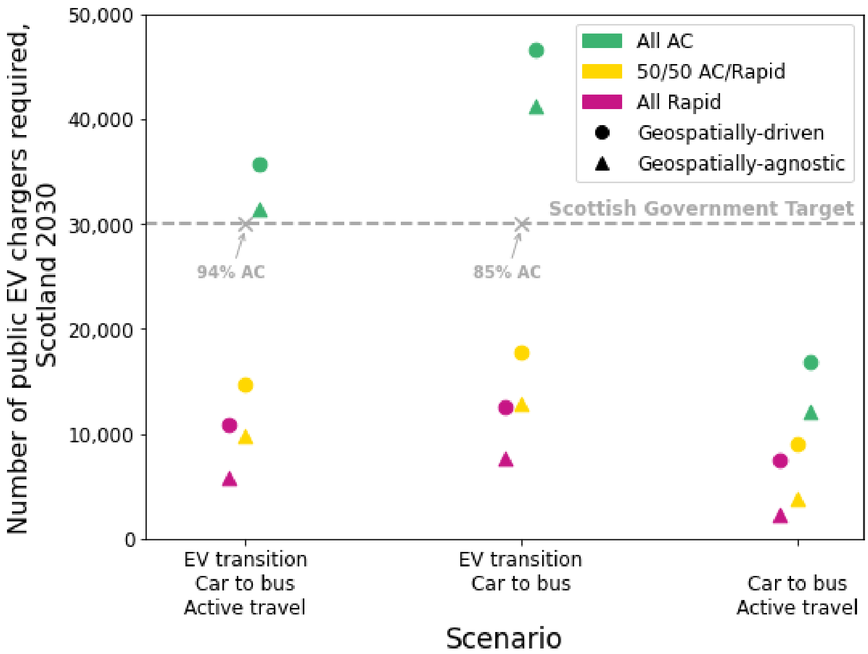

Figure 5.5: The charger population required by 2030 in Scotland under the scenarios for charger technology and sustainable intervention adoption where the service area of chargers is 5km wide

determined geospatially-agnostically to 16,796 chargers in the 'all AC' case determined by the geospatially-driven approach.

Therefore, in the case where further intervention is not taken to bolster EV adoption, the government targeted 30,000 chargers would likely be well above what is required in 2030. However, given the particular effectiveness of the EV transition in the Scottish context found in Chapter 3, supporting the transition to EVs is likely to be a critical strategic decision that will enable the emission reductions required to meet governmental targets. Assuming this is the case it will be important to achieve a charger population that will support the EV transition. Since, as mentioned, only the 'all AC' cases exceed a charger population of 30,000 for the scenarios including the EV transition, it is likely that the Scottish Government's target for charging provision is broadly sufficient to realise emission reduction targets. However, the charger populations projected are based on the achievement of the interventions included, namely modal shifting of car journeys under 10km to active travel, modal shifting of car journeys between 10 and 40km to bus and a 50% reduction is petrol/diesel cars with these being replaced by EVs. Therefore, the extent to which these interventions are achieved will likely impact the number of chargers required. Particularly, as mentioned in Section 2.1, there are many barriers to modal shifting from the private car to more sustainable modes including safety concerns [54], cost and availability of services [52], and adverse weather conditions [177]. Should the modal shifts outlined in the considered scenarios not be fully achieved, it is likely that additional chargers will be required as there will be increased car reliance.

In terms of differences between geospatially-agnostic and geospatially-driven results, as expected, the charger population required was larger when determined through the geospatially-driven approach in all cases. The difference between the number of chargers required, comparing geospatially-agnostic and geospatially-driven results for each scenario, ranged from 4,280 chargers to 5,350 chargers. The average difference in the number of chargers estimated for each scenario comparing geospatially-driven and geospatially-agnostic results is 4,948 chargers. Interestingly, the disparity between geospatially-driven and geospatially-agnostic results is almost constant across all scenarios. This highlights that dispersion of the population in Scotland has a reasonably significant impact on the public charger population required and is an important consideration in predicting public charging requirements in the Scottish context.

Additionally, the charger technology adopted has a strong impact on the overall charger population required. Across all scenarios, significantly more chargers are required in the 'all AC' cases compared to the 'all rapid' cases. Specifically, comparing the geospatially-driven results for the different scenarios, there is an average increase of 207% in the number of chargers required in the 'all AC' cases compared to the 'all rapid' cases. In terms of the split of AC versus rapid technologies required for the government targeted 30,000 chargers, the constant spatial effect mentioned above allows geospatially-agnostic values to be used in this calculation. Subtracting the average spatial effect from 30,000 chargers gives the corresponding geospatially-agnostic charger population. Then, using Equation 5.8 (see Section 5.2.1), the 'all rapid' case for each scenario is converted to a split of AC and rapid chargers that totals the geospatially-agnostic charger population that corresponds to 30,000 chargers accounting for the spatial effect. This gives the overall proportion of AC versus rapid chargers for a charger population of 30,000 that accounts for population dispersion, assuming that the additional chargers due to the spatial effect also have the same proportion of AC versus rapid chargers. It was found that in the scenario 'EV transition + car to bus + active travel' a minimum of 6% of chargers should be rapid while in the scenario 'EV transition + car to bus' a minimum of 15% of chargers should be rapid. As found in Chapter 4, 77% of chargers on ChargePlace Scotland network were AC. Therefore, the trend of a high proportion of AC chargers on the public network could be retained as the charger population expands to 30,000 chargers. These observations will be revisited in Section 5.4.

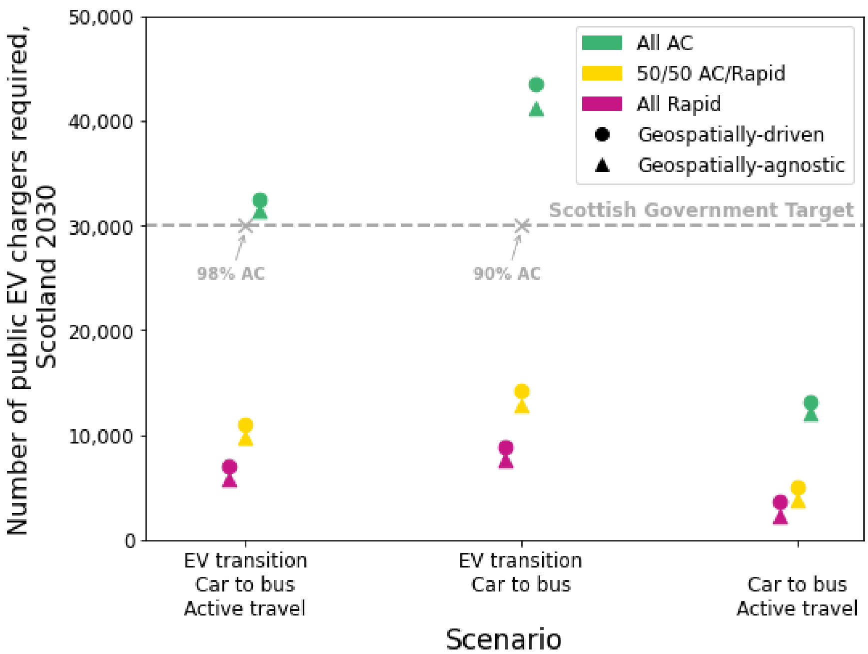

Figure 5.6: The charger population required by 2030 in Scotland under the scenarios for charger technology and sustainable intervention adoption where the service area of chargers is 10km wide

Increasing the distance at which a charger is still considered to be accessible to 10km (via the grid size of the spatial analysis) gave a lower number of chargers required found through the geospatially-driven analysis in each scenario and therefore a smaller gap between geospatially-agnostic and geospatially-driven results, as expected. Figure 5.6 summarises the results using the 10km hexagonal grid. The charger population required for scenario 'EV transition + car to bus + active travel' ranged from 5,841 chargers in the 'all rapid' case determined geospatially-agnostically to 32,503 chargers in the 'all AC' case determined by the geospatially-driven approach. For the scenario 'EV transition + car to bus', the charger population required ranged from 7,658 chargers in the 'all rapid' case determined geospatially-agnostically to 43,480 chargers in the 'all AC' case determined by the geospatially-driven approach. The charger population required for scenario 'car to bus + active travel' ranged from 2,237 chargers in the 'all rapid' case determined geospatially-agnostically to 13,186 chargers in the 'all AC' case determined by the geospatially-driven approach.

The difference between the number of chargers required comparing geospatially-agnostic and geospatially-driven results for each scenario ranged from 1,035 chargers to 2,224 chargers. The average difference in the number of chargers estimated for each scenario comparing geospatially-driven and geospatially-agnostic results is 1,324 chargers. These results indicate that there is a strong sensitivity to the range at which a charger is considered as accessible. The full set of results including those pertaining to both 5km and 10km hexagonal grids are given in Table 5.3.

It is important to bear in mind the limitations of the research methodology, outlined in Section 5.2.3, including the assumptions regarding charger operational hours and the population reliant on public chargers. In particular, the geospatially-driven analysis accounts only for population dispersion based on the usual resident population, meaning impacts of tourism are not considered. Therefore, certain areas may experience seasonal pressure on infrastructure and more chargers may be required to mitigate this issue. This effect may be more prominent in rural and remote areas as many tourist sites in Scotland (e.g. Loch Lomond, Glencoe, the Cairngorms) are located in these regions.

Table 5.3: Geospatially-agnostic and geospatially-driven (using both 5km and 10km hexagonal grids) results, including the quantified disparity between charger populations projected using the different methods

Scenario	**Geospatially-driven Charger Population, 5km (chargers)**	**Geospatially-driven Charger Population, 10km (chargers)**	**Geospatially-agnostic Charger Population (chargers)**	**Difference in number of chargers geospatially-driven vs agnostic, 5km (chargers)**	**Difference in number of chargers geospatially-driven vs agnostic, 10km (chargers)**
Active travel + car to bus, all AC	16,796	13,186	12,049	4,747	1,137
Active travel + car to bus, all rapid	7,546	3,579	2,237	5,309	1,342
Continued on next page...					

Scenario	**Geospatially-driven Charger Population, 5km (chargers)**	**Geospatially-driven Charger Population, 10km (chargers)**	**Geospatially-agnostic Charger Population (chargers)**	**Difference in chargers geospatially-driven vs agnostic, 5km**	**Difference in chargers geospatially-driven vs agnostic, 10km**
Active travel + car to bus, 50/50 AC/rapid	8,956	5,062	3,775	5,181	1,287
Active travel + car to bus + EV transition, all AC	35,748	32,503	31,468	4,280	1,035
Active travel + car to bus + EV transition, all rapid	10,892	7,081	5,841	5,051	1,240
Continued on next page...					

Scenario	Geospatially-driven Charger Population, 5km (chargers)	Geospatially-driven Charger Population, 10km (chargers)	Geospatially-agnostic Charger Population (chargers)	Difference in chargers geospatially-driven vs agnostic, 5km	Difference in chargers geospatially-driven vs agnostic, 10km
Active travel + car to bus + EV transition, 50/50 AC/rapid	14,702	11,045	9,857	4,845	1,188
Car to bus + EV transition, all AC	46,606	43,480	41,256	5,350	2,224
Car to bus + EV transition, all rapid	12,591	8,859	7,658	4,933	1,201
Continued on next page...					

Scenario	**Geospatially-driven Charger Population, 5km (chargers)**	**Geospatially-driven Charger Population, 10km (chargers)**	**Geospatially-agnostic Charger Population (chargers)**	**Difference in chargers geospatially-driven vs agnostic, 5km**	**Difference in chargers geospatially-driven vs agnostic, 10km**
Car to bus + EV transition, 50/50 AC/rapid	17,761	14,189	12,923	4,838	1,266

5.4 Implications for Policy, Practice and Future Work

The results of this chapter have important implications for policy and practice relating to development of the public charging network in Scotland in line with 2030 requirements. Specifically, there are implications for charging requirement quantification methods, charger technology investments and organisation of public charging network models. These implications are summarised in Figure 5.7. Firstly, as mentioned in Section 5.3, it is likely that the Scottish Government's planned rollout of an additional 24,000 chargers (to bring the overall charger population to circa 30,000 chargers) by 2030 will be sufficient. However, this rollout is only of value to the Scottish public and the realisation of emission reduction targets if the transition to EVs and the other sustainable transport interventions (i.e. modal shifts) are also achieved. Equitable development of the public charging network will be a critical component in the facilitation of an inclusive EV transition, however, it will be important to pay attention to how this may also support modal shifting of car journeys to active travel and public transport. This may involve the prioritisation of charger deployment at public transport hubs or park and ride/stride programmes.

Additionally, comparing the results of the geospatially-agnostic and geospatially-driven analysis where the service area of chargers was 5km, the disparity in charger population required under the different scenarios was circa 5,000 chargers. This indicates that, when seeking to quantify charging requirements in the Scottish context, a simpler geospatially-agnostic analysis can be conducted and the value of 5,000 chargers can be added to the output to account for the effects of population dispersion. This finding therefore has valuable modelling applications, with the potential to enhance the accuracy and representativeness of charger requirements models without necessarily increasing their complexity. Spatial impacts were found to be non-negligible, hence, ensuring that population dispersion is considered in quantifying public charging requirements will be key to enabling equitable geographic access to chargers. However it is important to bear in mind that, as mentioned in Section 5.3, the geospatial analysis has a strong sensitivity to the acceptable service range of chargers.

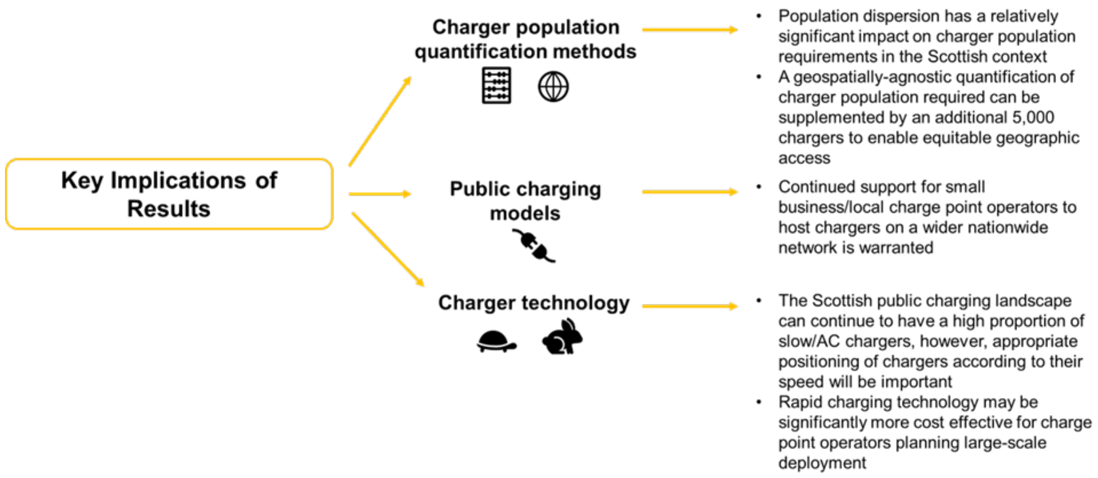

Figure 5.7: Summary of the key implications the results of this chapter have for policy and practice

Regarding charger technology, due to the much smaller charger population required in the ‘all rapid’ cases compared to the ‘all AC’ cases, investing more dominantly in rapid charging infrastructure may become more cost effective for charge point operators seeking to deploy chargers on a large scale, despite the larger upfront cost of this technology. The potential benefits of investing more heavily in one charger technology over another highlights the importance of careful planning, accurate charger population estimates and the careful placement of chargers to ensure chargers can effectively meet the needs of users. Specifically, AC chargers should be located at areas associated with long stays (e.g. residential areas, workplaces, public transport hubs) due to their lower charging speeds while rapid chargers should be located at areas associated with short stays (e.g. supermarkets, service stations, cafes/restaurants) due to their faster charging speeds and to prevent overstay behaviour which can lead to underutilisation of chargers. As identified, reaching the government targeted charger population of 30,000 means a relatively small number of rapid chargers can be deployed. A network that is predominantly comprised of AC chargers means identifying suitable charging locations that tend to incur longer sojourns should be a priority. Meanwhile, careful and intentional planning will be needed to ensure that the potentially small number of rapid chargers to be sited are placed in optimal locations in an equitable manner.

Additionally, as mentioned in Section 1.2, AC chargers generally have a substantially lower upfront cost associated with the charging equipment and often their installation [38, 39]. Therefore, aiming for a high proportion of AC chargers on the Scottish public charging network may enable the participation of smaller business in public EV charging provision should a network business model that allows individual owners and operators to host chargers on a wider network (such as the ChargePlace Scotland model) continue to be available. This possibility may be particularly important to businesses that will be directly involved in the EV transition such as small, independent car dealerships who may be looking to diversify their revenue streams by entering the public charging landscape. In turn, the Scottish Government highlight the need for private investment [26] to support development of public charging provision, so supporting diverse businesses of all sizes to participate in the public charging ecosystem may relieve pressure on the public sector. As mentioned in Section 2.4, the ChargePlace Scotland network faces an uncertain future due to the planned cessation of funding to support charge point owners and operators to host a charger on the network. Continuing to provide some form of support to charge point operators to integrate chargers on the ChargePlace Scotland network, or another network featuring a similar model, may be beneficial to the overall transition to EVs in Scotland.

Future work could explore future public charging network models and configurations in Scotland that could facilitate the involvement of smaller business in the role of charging provision as the ChargePlace Scotland model is retired. Such work could investigate how a balance could be struck between providing support for the installation of chargers whilst ensuring additional pressure is not placed on public funds through development of a cost and constraints model. Additionally, future work could expand the present analysis through the inclusion of other important factors such as traffic flows, localised tourism impacts and electrical grid constraints. Further work could also seek to identify optimal locations for future charger deployment on a regional basis in the Scottish context. Furthermore, future work is warranted to explore the acceptable travel distance between chargers in the Scottish context. Such work may require detailed road network data to accurately map travel time between chargers and different origin and/or destination points.

The results of this analysis may provide some insight for countries with similar population structures, EV adoption rates and car use patterns. However, other factors unique to Scotland (e.g. socioeconomic dynamics, the uncommon rollout strategy of public charging etc.) may mean the resulting recommendations are specific to the Scottish context and are of limited relevance to other areas. However, should the relevant data be available for other countries, the methods used could be repeated and applied to other areas.

5.5 Conclusions

This chapter has estimated the charger population required by 2030 in Scotland to enable achievement of emission reduction targets using both geospatially-agnostic and geospatially-driven techniques. A geospatially-agnostic approach based on car kilometres travelled has been used to inform Scottish Government charging provision targets, however there is a risk that such an approach may underestimate the charger population required to enable equitable geographic access to chargers as population dispersion is not considered.

In line with Research Question 3 (as outlined in Chapter 1), results indicated that, when estimated using the geospatially-driven analysis with a 5km hexagonal grid (see Section 5.2.2), the charger population required by 2030 ranged from 7,546 chargers to 46,606 chargers depending on the charger technology and sustainable intervention adoption scenario. Additionally, there was an almost constant disparity between the charger population estimated using the geospatially-driven and geospatially-agnostic approaches across all scenarios, with the geospatially-driven analysis estimating that the geospatially-agnostic charger population should be supplemented by an additional circa 5,000 chargers to facilitate equitable geographic access. Furthermore, the charger technology type was highly impactful on the overall charger population required, with 'all AC' cases on average necessitating a 207% increase in the number of chargers compared to the 'all rapid' cases. However, to achieve a charger population of 30,000 chargers in line with the Scottish Government's target, an AC dominant network can be retained with the minimum percentage of rapid chargers required estimated to be between 6% and 15%. The geospatially-driven analysis was also undertaken using a 10km grid and it was found that the analysis had a strong sensitivity to the acceptable service range of chargers.

The implications of the results for policy and practice include that the Scottish Government's charging infrastructure installation targets are likely sufficient to enable achievement of emission reduction targets, however, the charger populations estimated in this chapter require the achievement of the sustainable transport interventions outlined in the scenarios. Additionally, population dispersion was found to have an impact on the charger population required in the Scottish context so will be an important consideration in terms of ensuring equitable geographic access to chargers. The almost constant disparity between geospatially-driven and geospatially-agnostic analyses indicates that simpler quantifications of charger population required based on car kilometres travelled can be conducted and that around 5,000 chargers can be added to this estimation to enable the network to be geographically inclusive. Additionally, maintaining a high proportion of AC chargers on the network may facilitate the participation of smaller businesses in the public charging market. Identifying appropriate locations for AC chargers that correspond to long-stay locations will also become critical. It is important to bear in mind the limitations of the analyses outlined in this chapter (see Section 5.2.3), particularly the fact that traffic flows and electrical grid constraints are not considered.

Chapter 6

Conclusion

The imminent threat that climate change poses to humankind makes prompt action to reduce emissions crucial. The transport sector, particularly road transportation, poses a major threat to the achievement of net zero due to its significant polluting power. As a result, the Scottish Government has set a 2045 legally-binding deadline to reach net zero alongside transport-specific goals, namely a 56% reduction in transport-related emissions and 20% reduction in car kilometres travelled by 2030. Electrification of private cars is thought to be a key component in enabling emissions reductions. Additionally, the Scottish Government has also outlined other interventions envisioned to facilitate crucial emissions reductions in the transport sector, specifically modal shifting of some car journeys to active travel and public transport, and electrification of the bus fleet. With deadlines for government targets rapidly approaching and with global temperatures continuing to rise, understanding the efficacy of planned interventions in enabling emissions reductions is crucial.

Therefore, this thesis firstly aimed to explore how critical the transition to EVs is to achieving Scottish Government emission reduction targets compared to other planned interventions. Chapter 3 developed, validated and applied a system dynamics model of the Scottish road passenger transport sector to investigate the likely ability of the following interventions to reduce emissions: modal shifting of car journeys under 10km to active travel; the modal shifting of car journeys between 10 and 40km to bus transportation; achieving a 60% electrification of the bus fleet by 2024; and a 50% reduction in petrol/diesel cars by 2030, with these cars being replaced by EVs. The performance of the interventions was explored in the context of the Scottish Government transport emission and car kilometre reduction targets. It was found that certain combinations of the interventions explored would be able to achieve the government mandated 56% reduction in emissions by 2030, however, at least three interventions were required in each case, highlighting the need for a broad programme of measures. The transition to EVs was found to drive the most significant emissions reduction, indicating policy supporting this transition should likely be prioritised. Ensuring the EV transition is equitable will be crucial. Actions such as increasing visibility of and government support for zero-emission car clubs, which can act as an alternative to car ownership, could be beneficial. Furthermore, developing an inclusive public charging network will be vital to removing barriers to EV access particularly for those without private charging options or those who tend to complete longer car journeys.

The conclusion drawn from Chapter 3, indicating that the transition to EVs is likely critical in the context of achieving Scottish Government targets, gave rise to the next aim of this thesis which was to investigate the current state of public EV charging in Scotland in order to gain insight into how the public network may be developed to support an equitable EV transition. The Scottish Government have highlighted the importance of their aim and commitment to achieve an equitably accessible and inclusive public charging network. Chapter 4 developed and analysed a dataset of EV charging sessions taking place on the ChargePlace Scotland network, spanning a total of 2,786 chargers over the period from October 2022 to March 2024. The current distribution of chargers, trends in charging times, the impact of tariff introduction, and the characteristics associated with the most utilised chargers were explored in this chapter and the subsequent implications for policy and practice surrounding enabling an equitable transition were discussed. 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. This disparity in trends suggests that 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. Additionally, the 20% least deprived areas had the fewest chargers, indicating that in terms of social deprivation Scotland appears to deviate from trends found in other international contexts where chargers tend to be disproportionately focused in the least deprived areas. The unconventional rollout strategy for public charging in Scotland, where charge point operators were provided government funding to install chargers, may have contributed positively to this trend. Other findings included that 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, although there were disparities in patterns between different area types with the most rural regions showing distinct usage patterns. This highlights that localised approaches to actions aiming to change charging behaviours are likely necessary. Additionally, 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. It was also found that 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.

The final aim of this thesis was then to explore the charger population required by 2030 to provide equitable geographic access to chargers in Scotland, which formed the focus of Chapter 5. The analysis outlined in Chapter 5 utilised outputs from Chapters 3 and 4. Different scenarios for charger technology adoption and sustainable intervention adoption were considered when projecting the charger population required and two approaches were taken. The first was a geospatially-agnostic approach based on EV kilometres travelled, similar to the approach taken by the Climate Change Committee's recommendation that underpinned the Scottish Government's commitment to install an additional 24,000 chargers by 2030. Since such an approach assumes all activity takes place at a central point, the geographic dispersion of population is not considered. Therefore, a geospatially-driven approach, incorporating GIS techniques to account for population dispersion, was also taken. It was found that the public charger population required to support achievement of emission reduction targets, accounting for population dispersion, was between 7,546 and 46,606 chargers depending on the charger technology and sustainable intervention adoption scenario. Results generally indicated that the Scottish Government target for infrastructure provision will likely be adequate. The charger technology adopted had a significant impact on the overall charger population required, with 'all AC' scenarios requiring an average of 207% more chargers than 'all rapid' cases. Aiming for an overall charger population of 30,000 as mandated by the government target will require a minimum of between 6% and 15% of rapid chargers, meaning an AC dominant network can be retained. Furthermore, the average difference between geospatially-agnostic and geospatially-driven results, when the service area of chargers had a 5km diameter, was 4,948 chargers. This indicates that a geospatially-agnostic quantification of charger population required should be supplemented by approximately 5,000 chargers to ensure there is equitable geographic access in the Scottish context.

Therefore, in summary, the key findings of this thesis in line with the Research Questions outlined in Chapter 1 are:

1. The transition to EVs is likely highly critical in the context of achieving the 2030 Scottish Government sustainable transport targets. Results from Chapter 3 show that the transition to EVs was predicted to give the most significant emission reduction compared to the other interventions considered, namely modal shifting of shorter car journeys to active travel; modal shifting of medium-length car journeys to bus; and electrification of the bus fleet. However, it was found that no single intervention was predicted to sufficiently reduce emissions or car kilometres in line with the government targets and that a combination of interventions will likely be required, highlighting the necessity for a broad package of interventions.

2. In relation to the current state of public charging in Scotland, the following insights were gained in terms of its physical arrangement in terms of urban/rural context, social deprivation and geographical accessibility:

- Chargers were found generally to be more concentrated in urban areas although rural areas tended to have more chargers per head of population
- Areas falling within the 20% least deprived had the fewest chargers
- Areas falling within the 20% most accessible had the most chargers although this was closely followed by areas falling within the 20% least accessible

Additionally, observations made surrounding public charging behaviour in Scotland included:

- Generally, weekdays tended to feature more charging sessions than weekends
- Charging times tended to align with times of peak energy demand although different areas exhibited different trends with the most rural areas showing the greatest disparity and having sessions more concentrated to the middle of the day
- The East Lothian trial of time-of-use tariffs saw a shift from 19.2% of sessions to 15.7% of sessions starting between the hours the increased tariff was active
- 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
- Generally, rapid chargers were found to be more well utilised than AC chargers with 35% of AC chargers being used at least once daily compared to 86% of rapid/ultra-rapid chargers
- Most utilised chargers tended to be in urban, geographically accessible areas

Related implications of these findings for realising an equitable transition to EVs include:

- Behaviour changes will likely be necessary to ease pressure on infrastructure at times of peak demand, however a localised approach is likely needed and careful attention should be paid to ensuring any regional disparities are equitable

- Government support should be targeted for charger deployment in the areas identified as being less commercially viable
- Development of metrics for holistic quantification of charger provision and quality will be important for guiding public charging development

3. As outlined in Chapter 5, the geospatially-driven quantification of charging requirements by 2030 in Scotland gives an understanding of the charger population required to enable equitable geographic access. Geospatially-driven results ranged from a charger population of 7,546 chargers to 46,606 chargers when the service area of chargers was 5km in diameter. Scenarios including the EV transition required more chargers than the scenario without and on average 'all AC' cases required 207% more chargers than 'all rapid' cases. Comparing geospatially-agnostic and geospatially-driven approaches, the effect of population dispersion necessitated that geospatially-agnostic quantifications were supplemented with circa 5,000 chargers to enable equitable geographic access.

6.1 Further Work

The research outlined in this thesis also presents possible directions for future work. Overall, the aim of the research was to provide insights surrounding the EV transition and public EV charging specific to Scotland. While some findings may provide insight for countries with comparable demographics, EV uptake and travel behaviours, some observations in this thesis may be unique to Scotland. Should data be available, the methods could be repeated and applied to other geographical contexts to gain more specific insights.

As found in Chapter 3, the modal shifting of medium-length car journeys was also found to be an effective intervention in terms of enabling emissions reductions. Therefore, further work is warranted to determine the most cost-effective and efficient pathways to delivering enhancements to public transport provision such as ensuring public transport can meet the diverse needs of different groups, addressing barriers to access such as safety concerns and cost, and developing nationwide or interoperable regional MaaS or integrated ticketing systems. Additionally, further research is required to understand how travel behaviour and mode choice can effectively be influenced by supporting policies and actions to enable these modal shifts in the Scottish context. Exploring the likelihood and extent to which the behavioural change considered in Chapter 3 (i.e. modal shifting away from the private car and transitioning towards EVs) can be achieved, particularly in periods of adverse weather, would be valuable. Specifically, such further work could explore pathways to enabling these changes such as social marketing programmes and other policy packages. Additionally, the developed model presented in Chapter 3 could be expanded and developed to be applicable to give insight into other relationships and complexities in the transport sphere such as policy surrounding land use and allocation of space for cars. This could involve the addition of further variables, feedback loops and structures, however, such extensions would require additional data and careful model development to ensure the validity of results is not compromised and any limitations can be understood.

Furthermore, Chapter 4 found that different trends were observed in charging provision across urban and rural areas depending on whether this was quantified by the absolute number of chargers or the number of chargers per 100,000 people. Further work could aim to develop a suitable metric, or set of metrics, that can provide a holistic understanding of charging provision across different regions. Additionally, further research is warranted to develop a means of measuring the quality of charge points, accounting for safety aspects and proximity to services. This may inform interventions which could encourage greater utilisation of chargers that are underused or that experience low demand at night. Such work may require further data collection concerning the immediate environment of chargers. Also, collection of additional public charging data from the user's perspective, rather than the charger's perspective, could be beneficial in facilitating a wider understanding of charging behaviours. Similarly, this may require collection of further data including user identification numbers (perhaps from user access cards which facilitate use of the network) and other information pertaining to users such as their home or work address postcode to understand their charging habits in terms of choice of charger in relation to their usual home/workplace location and to add socioeconomic context (e.g. urban/rural classification and deprivation) to the areas in which they operate. Such personal information would need to be handled with care and due diligence. Further research is also warranted to gain a better understanding of the impact of tariff programmes aiming to facilitate behavioural changes in the Scottish context. The analysis outlined in Chapter 4 included exploration of a pilot time-of-use tariff scheme applied to a small number of chargers in one local authority, however further work could 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. The analysis in Chapter 4 specifically considered data from the publicly funded ChargePlace Scotland public network. As more public chargers on charging networks driven by private investment emerge, and increase their contribution to the overall Scottish public charging network, future work including data from these chargers on various networks is warranted to provide broader insight to public charging in Scotland.

Additionally, the analysis conducted in Chapter 5 estimated charger population required based on the dispersion of population. Further work could seek to include additional data on other important aspects such as traffic flows, electrical grid constraints and tourism impacts. In particular, potential impacts of tourism on charging requirements may disproportionately affect more rural and remote regions, making it important to explore these impacts in future work to ensure rural residents do not experience additional barriers to public charging due to the additional demand brought by seasonal visitors. Future research could also aim to identify optimal locations for the charger population identified in this analysis and could seek to better understand acceptable travel distances between chargers in the Scottish context. Further work is also warranted to explore future business models for public charging in Scotland that could continue to facilitate involvement of smaller businesses and local authorities in the role of charging provision while minimising public expenditure. This type of work may become particularly important as the ChargePlace Scotland model is retired and EV adoption continues to grow.

Appendix A

Scottish Household Survey Data Comparison with UK National Travel Survey Data

Section 3.2.3 used Scottish Household Survey data on distance of car journeys (see Table 3.5) to find the proportion of total distance travelled in sub-10km and 10km to 40km car journeys. Using the process outlined via Equations 3.1 to 3.11, these values were found to be 0.1325 and 0.4414 respectively. To compare these values with UK travel patterns, the same process outlined in Section 3.2.3 can be undertaken using data from the UK National Travel Survey [215]. Table A.1 shows the UK equivalent data to that given in Table 3.5.

Undertaking the processes outlined in Section 3.2.3 using the data in Table A.1 gives values of 0.14431 and 0.48071 for the proportion of total distance travelled in sub-10km and 10km to 40km car journeys respectively. Additionally, the mean car journey distance was 16.7km according to the Scottish Household Survey and 13.2km according to the UK National Travel Survey (see Tables 3.5 and A.1) and Figure A.1 shows a comparison of the reported data from both surveys, highlighting that the results and overall travel patterns are similar.

Table A.1: Data from [215] on average journey distance by mode

Proportion of journeys	**Journey distance by car/van as a driver (km)**
0.07	1.609
0.24	3.218
0.58	8.045
0.79	16.09
0.94	40.225
0.98	80.45
0.99	160.9
Mean	13.194

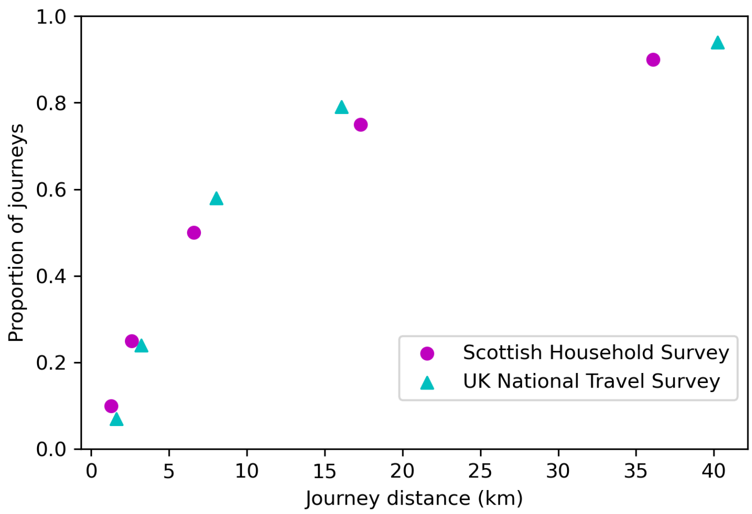

Figure A.1: Comparison of data from the UK National Travel Survey [215] and Scottish Household Surveys [175] on car journey distances up to 40km

Appendix B

Chargers per 100,000 People in Scottish Index of Multiple Deprivation and Geographical Accessibility Index Quintiles

Figures B.1 and B.2 give the number of chargers per 100,000 people in each quintile of the Scottish Index of Multiple Deprivation and Geographical Accessibility Index, respectively.

Appendix B. Chargers per 100,000 People in Scottish Index of Multiple Deprivation and Geographical Accessibility Index Quintiles

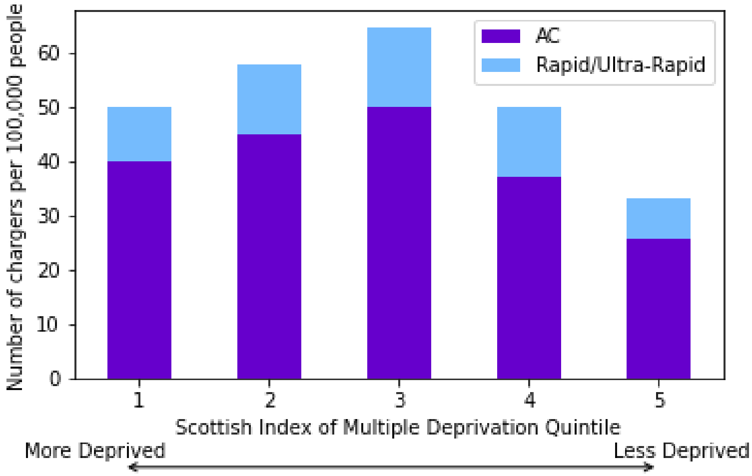

Figure B.1: The number of EV chargers per 100,000 people on the ChargePlace Scotland public network found in each Scottish Index of Multiple Deprivation quintile, where a lower quintile generally indicates a more deprived area, and a higher quintile generally indicates a less deprived area

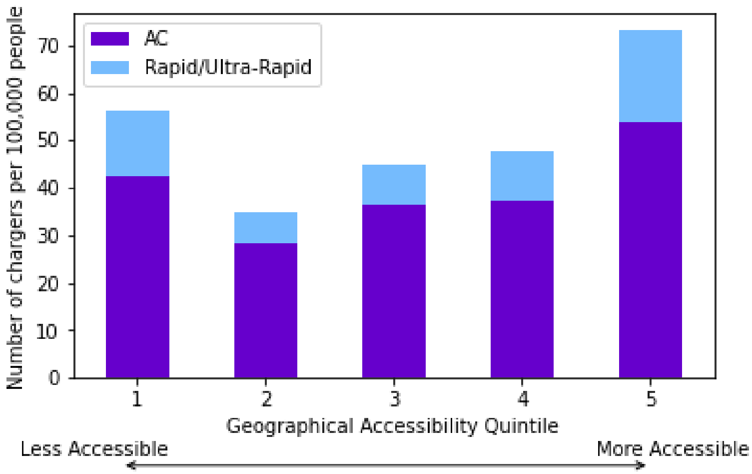

Figure B.2: The number of EV chargers per 100,000 people on the ChargePlace Scotland public network found in each Geographical Accessibility Index quintile, where a lower quintile generally indicates a less accessible area, and a higher quintile generally indicates a more accessible area

Bibliography

[1] United Nations, "Causes and effects of climate change," Feb. 2025. [Online]. Available: https://www.un.org/en/climatechange/science/causes-effects-climate-change

[2] ——, "The paris agreement," Feb. 2025. [Online]. Available: https://www.un.org/en/climatechange/paris-agreement

[3] World Meteorological Organization, "Wmo confirms 2024 as warmest year on record at about 1.55°c above pre-industrial level," Jan. 2025. [Online]. Available: https://wmo.int/news/media-centre/wmo-confirms-2024-warmest-year-record-about-155degc-above-pre-industrial-level

[4] Scottish Government. Scottish greenhouse gas statistics 2021. [Online]. Available: https://www.gov.scot/publications/scottish-greenhouse-gas-statistics-2021/pages/3/

[5] Transport Scotland. Scottish transport statistics 2022. [Online]. Available: https://www.transport.gov.scot/publication/scottish-transport-statistics-2022/chapter-13-environment/

[6] Scottish Government. About net zero. [Online]. Available: https://netzeronation.scot/about

[7] J. Woodcock, P. Edwards, C. Tonne, B. G. Armstrong, O. Ashiru, D. Banister, S. Beevers, Z. Chalabi, Z. Chowdhurry, A. Cohen, O. Franco, A. Haines, R. Hickman, G. Lindsay, I. Mittal, D. Mohan, G. Tiwari, A. Woodward, and I. Roberts,

"Public health benefi ts of strategies to reduce greenhouse-gas emissions: urban land transport," *The Lancet*, vol. 374, no. 9705, pp. 1930–1943, 2009.

[8] J. Milner, I. Hamilton, J. Woodcock, M. Williams, M. Davies, P. Wilkinson, and A. Haines, "Health benefits of policies to reduce carbon emissions," *BMJ*, vol. 368, no. 6758, 2020.

[9] M. J. Douglas, J. Teuton, A. MacDonald, B. Whyte, and A. L. Davis, "Road space reallocation in scotland: A health impact assessment," *Journal of Transport Health*, vol. 30, no. 101625, 2023.

[10] Transport Scotland. Mission zero for transport. [Online]. Available: https://www.transport.gov.scot/our-approach/mission-zero-for-transport/#overview

[11] ——. A route map to achieve a 20 per cent reduction in car kilometres by 2030. [Online]. Available: https://www.transport.gov.scot/publication/a-route-map-to-achieve-a-20-per-cent-reduction-in-car-kilometres-by-2030/

[12] Scottish Government. Securing a green recovery on a path to net zero: climate change plan 2018–2032 - update. [Online]. Available: https://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/pages/2/

[13] Audit Scotland. Minimal progress on reducing car use. [Online]. Available: https://audit.scot/news/minimal-progress-on-reducing-car-use

[14] AECOM. Travel demand management options study. [Online]. Available: https://www.transport.gov.scot/publication/travel-demand-management-options-study/

[15] The Scottish Parliament. Public audit committee [draft]. [Online]. Available: https://www.parliament.scot/chamber-and-committees/official-report/search-what-was-said-in-parliament/PA-23-04-2025?meeting=16382&iob=139934

[16] Transport Scotland. National transport strategy. [Online]. Available: https://www.transport.gov.scot/media/47052/national-transport-strategy.pdf

[17] ——. Switched on scotland: A roadmap to widespread adoption of plug in vehicles. [Online]. Available: https://www.transport.gov.scot/media/30506/j272736.pdf

[18] ——. National transport strategy (nts2) - second delivery plan - 2022-2023. [Online]. Available: https://www.transport.gov.scot/media/51675/national-transport-strategy-nts2-second-delivery-plan-2022-2023.pdf

[19] Z. Christoforou, A. de Bortoli, C. Gioldasis, and R. Seidowsky, "Who is using e-scooters and how? evidence from paris," *Transportation Research Part D: Transport and Environment*, vol. 92, no. 102708, 2021.

[20] P. Cuffe, "Flexible mobility in the smart city: the role of small personal electric vehicles," in *eseia Conference on Smart Energy Systems in Cities*, Dublin, Ireland, 2018.

[21] A. Moseman. Are electric vehicles definitely better for the climate than gas-powered cars? [Online]. Available: https://climate.mit.edu/ask-mit/are-electric-vehicles-definitely-better-climate-gas-powered-cars

[22] International Energy Agency. Global ev outlook 2024: Outlook for emissions reductions. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2024/outlook-for-emissions-reductions

[23] Element Energy. Decarbonising the scottish transport sector. [Online]. Available: https://www.transport.gov.scot/media/50354/decarbonising-the-scottish-transport-sector-summary-report-september-2021.pdf

[24] Zapmap. Zap-map releases most comprehensive survey of ev drivers in the uk. [Online]. Available: https://www.zap-map.com/news/zap-map-releases-ev-charging-survey

[25] S. Hardman, K. L. Fleming, E. Khare, and M. M. Ramadan, "A perspective on equity in the transition to electric vehicle," *MIT Science Policy Review*, vol. 2, pp. 46–54, 2021.

[26] Transport Scotland. A network fit for the future: Vision for scotland's public electric vehicle charging network. [Online]. Available: https://www.transport.gov.scot/media/53632/a-network-fit-for-the-future-final-vision-for-scotland-s-public-electric-vehicle-charging-network.pdf

[27] National Association of Colleges and Employers. What is equity? [Online]. Available: https://www.naceweb.org/about-us/equity-definition

[28] Cambridge Free English Dictionary and Thesaurus. Equity. [Online]. Available: https://dictionary.cambridge.org/dictionary/english/equity

[29] H. A. U. Khan, S. Price, C. Avraam, and Y. Dvorkin, "Inequitable access to ev charging infrastructure," *The Electricity Journal*, vol. 35, no. 107096, 2022.

[30] F. Schulz and J. Rode, "Public charging infrastructure and electric vehicles in norway," *Energy Policy*, vol. 160, no. 112660, 2022.

[31] R. Wolbertus, M. Kroesen, R. van den Hoed, and C. G. Chorus, "Policy effects on charging behaviour of electric vehicle owners and on purchase intentions of prospective owners: Natural and stated choice experiments," *Transportation Research Part D: Transport and Environment*, vol. 62, pp. 283–297, 2018.

[32] B. J. Mortimer, C. Hecht, R. Goldbeck, D. U. Sauer, and R. W. D. Doncker, "Electric vehicle public charging infrastructure planning using real-world charging data," *World Electric Vehicle Journal*, vol. 13, no. 94, 2022.

[33] X. Liu, X. Sun, H. Zheng, and D. Huang, "Do policy incentives drive electric vehicle adoption? evidence from china," *Transportation Research Part A: Policy and Practice*, vol. 150, pp. 49–62, 2021.

[34] X. Zhao, X. Li, Z. Zhao, and T. Luo, "Media attention and electric vehicle adoption: Evidence from 275 cities in china," *Transportation Research Part A: Policy and Practice*, vol. 190, no. 104269, 2024.

[35] eDF. Electric car charging points. [Online]. Available: https://www.edfenergy.com/electric-cars/charging-points

[36] Idaho National Laboratory. Dc fast charge effects on battery life and performance study. [Online]. Available: https://avt.inl.gov/sites/default/files/pdf/vehiclebatteries/DCFC_Study_FactSheet_EOT.pdf

[37] C. Argue. How long do electric car batteries last? what analyzing 10,000 evs tells us. . . . [Online]. Available: https://www.geotab.com/blog/ev-battery-health/

[38] Cenex and Innovate UK. Ev charging in car parks. [Online]. Available: https://www.cenex.co.uk/app/uploads/2019/11/IUK-Car-Park-Study-V2.0-FINAL-marketing-version.pdf

[39] Cenex. Operating and charging. [Online]. Available: https://bett.cenex.co.uk/guidance/costs

[40] International Energy Agency. Global ev outlook 2025: Electric vehicle charging. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2025/electric-vehicle-charging

[41] International Council on Clean Transportation. Estimating electric vehicle charging infrastructure costs across major u.s. metropolitan areas. [Online]. Available: https://theicct.org/publication/estimating-electric-vehicle-charging-infrastructure-costs-across-major-u-s-metropolitan-areas/

[42] L. Hunter, R. Sims, and S. Galloway, "Open data to accelerate the electric mobility revolution: Deploying journey electric vehicle chargers in rural scotland," *IEEE Power Energy Magazine*, pp. 55–67, 2023.

[43] ChargePlace Scotland and Transport Scotland. Chargeplace scotland. [Online]. Available: https://chargeplacescotland.org/

[44] Scottish Futures Trust. Public ev charging in scotland: Insight report on tariffs. [Online]. Available: https://www.scottishfuturestrust.org.uk/storage/uploads/publicevcharginginscotlandinsightreportontariffsnovember2022.pdf

[45] Zapmap. Ev charging statistics 2024. [Online]. Available: https://web.archive.org/web/20241219130949/https://www.zap-map.com/ev-stats/how-many-charging-points

[46] Scottish Government. Stepping up action to net zero. [Online]. Available: https://www.gov.scot/news/stepping-up-action-to-net-zero/

[47] Scotland's Census and National Statistics. Scotland's census 2022 - rounded population estimates - data. [Online]. Available: https://www.scotlandscensus.gov.uk/2022-results/scotland-s-census-2022-rounded-population-estimates/

[48] GADM. Browse maps by country. [Online]. Available: https://gadm.org/maps.html

[49] Climate Change Committee. Progress in reducing emissions in scotland: 2023 report to parliament. [Online]. Available: https://www.theccc.org.uk/wp-content/uploads/2024/03/Progress-in-reducing-emissions-in-Scotland-2023-Report-to-Parliament.pdf

[50] M. J. Douglas, M. Higgins, H. Austin, G. Armour, R. Jepson, H. Thomson, and F. Hurley, "Health and transport: A guide. scottish health and inequalities impact assessment network," *Scottish Health and Inequalities Impact Assessment Network*, 2018.

[51] R. L. Mackett and R. Thoreau, "Transport, social exclusion and health," *Journal of Transport Health*, vol. 2, pp. 610–617, 2015.

[52] M. Martiskainen, D. Hopkins, G. A. T. Contreras, K. E. H. Jenkins, G. Mattioli, N. Simcock, and M. Lacey-Barnacle, "Eating, heating or taking the bus? lived experiences at the intersection of energy and transport poverty," *Global Environmental Change*, vol. 82, no. 102728, 2023.

[53] Sustrans. Transport poverty in scotland. [Online]. Available: https://www.sustrans.org.uk/media/2880/transport_poverty_in_scotland_2016.pdf

[54] K. S. Orr, E. W. Smith, M. Barry, and L. Sharp. Women's and girls' views and experiences of personal safety when using public transport. [Online]. Available: https://www.transport.gov.scot/publication/womens-and-girls-views-and-experiences-of-personal-safety-when-using-public-transport/

[55] K. Lucas, N. Cass, and M. Adeel, *Research Handbook on Energy and Society*. Edward Elgar, 2021, ch. Social divisions in energy justice and the transport sector: personal car ownership and use.

[56] J. Cludius, V. Noka, N. Unger, L. Delfosse, T. Dolinga, K. Schumacher, C. Suta, R. Lechtenfeld, A. Vornicu, A. Sinea, A. Serarols, M. Garcia, F. Giardina, K. Lucas, H. Radzuan, S. Bouzarovski, K. Krawiec, P. Chrzanowski, and K. Rucinski. Transport poverty: definitions, indicators, determinants, and mitigation strategies. [Online]. Available: https://www.transportpoverty.it/wp-content/uploads/Transport-poverty-definitions-indicators-determinants-and-mitigation-strategies.pdf

[57] K. Lucas and H. Adeogun. Low carbon transport for people on low incomes. [Online]. Available: https://www.jrf.org.uk/climate-change/low-carbon-transport-for-people-on-low-incomes

[58] K. Boyd, C. Calvillo, T. Mueller, X. Mu, and T. Zhu, "The intersection of fuel and transport policy in scotland: A review of policy, definitions and metrics," *Energies*, vol. 16, 2023.

[59] K. Lucas and K. Pangbourne, "Assessing the equity of carbon mitigation policies for transport in scotland," *Case Studies on Transport Policy*, vol. 2, pp. 70–80, 2014.

[60] P. Nakshi, K. Lucas, and S. Farber, "Travelling in the margins: Impacts of transport poverty on travel attitudes and behaviours," *Transportation Research Part A: Policy and Practice*, vol. 196, 2025.

[61] G. Fountas, A. Fonzone, and A. Olowosegun, “The impact of the cost-of-living crisis on travel choices: The case of scotland,” *Research in Transportation Economics*, vol. 110, 2025.

[62] Transport Scotland. £30 million to support the shift to zero emission transport. [Online]. Available: https://www.transport.gov.scot/news/30-million-to-support-the-shift-to-zero-emission-transport/

[63] ——. Maas investment fund - mobility as a service. [Online]. Available: https://www.transport.gov.scot/our-approach/mobility-as-a-service/maas-investment-fund-mobility-as-a-service/#62428

[64] N. Rabbitt and B. Ghosh, “Economic and environmental impacts of organised car sharing services: A case study of ireland,” *Research in Transportation Economics*, vol. 57, pp. 3–12, 2016.

[65] A. M. A. Vélez and A. Plepys, “Car sharing as a strategy to address ghg emissions in the transport system: Evaluation of effects of car sharing in amsterdam,” *Sustainability*, vol. 13, no. 2418, 2021.

[66] C. Cisterna, F. Bigi, F. Tinessa, and F. Viti, “Analysis of maas membership attributes: an agent-based approach,” *Transportation Research Procedia*, vol. 62, pp. 483–490, 2022.

[67] P. Labee, S. Rasouli, and F. Liao, “The implications of mobility as a service for urban emissions,” *Transportation Research Part D: Transport and Environment*, vol. 102, no. 103128, 2022.

[68] X. Zhao, C. Andruetto, B. Vaddadi, and A. Pernestål, “Potential values of maas impacts in future scenarios,” *Journal of Urban Mobility*, vol. 1, no. 100005, 2021.

[69] M. Orozoco-Fontalvo and F. Moura, “Refocusing maas approach: A brief,” *Transport Policy*, vol. 141, pp. 340–342, 2023.

[70] J. Pritchard, "Maas to pull us out of a car-centric orbit: Principles for sustainable mobility-as-a-service in the context of unsustainable car dependency," *Case Studies on Transport Policy*, vol. 10, pp. 1483–1493, 2022.

[71] Scottish Government and Ricardo and UK Centre for Ecology and Hydrology. Greenhouse gas emissions projections, scotland: Results of phase 1 and phase 2 modelling. [Online]. Available: https://www.gov.scot/binaries/content/documents/govscot/publications/research-and-analysis/2024/01/greenhouse-gas-emissions-projections-scotland-results-phase-1-phase-2-modelling/documents/greenhouse-gas-emissions-projections-scotland-results-phase-1-phas

[72] G. Broadbent, C. Allen, T. Wiedmann, and G. Metternicht, "The role of electric vehicles in decarbonising australia's road transport sector: modelling ambitious scenarios," *Energy Policy*, vol. 168, no. 113144, 2022.

[73] Scottish Government. Scottish energy statistics hub: Proportion of electricity generation by fuel. [Online]. Available: https://scotland.shinyapps.io/sg-scottish-energy-statistics/?Section=RenLowCarbon&Subsection=RenElec&Chart=ElecGen

[74] ——. Climate change monitoring report 2023. [Online]. Available: https://www.gov.scot/publications/climate-change-monitoring-report-2023/

[75] Electric Vehicle Database. Energy consumption of electric vehicles. [Online]. Available: https://ev-database.org/uk/cheatsheet/energy-consumption-electric-car

[76] UK Government. Vehicle licensing statistics data tables. [Online]. Available: https://www.gov.uk/government/statistical-data-sets/vehicle-licensing-statistics-data-tables

[77] L. Maybury, P. Corcoran, and L. Cipcigan, "Mathematical modelling of electric vehicle adoption: A systematic literature review," *Transportation Research Part D: Transport and Environment*, vol. 107, 2022.

[78] S. Maskrey, N. Mount, and C. Thorne, "Doing flood risk modelling differently: Evaluating thepotential for participatory techniques to broaden flood riskmanagement decision-making," *Journal of Flood Risk Management*, vol. 15, 2022.

[79] C. Domarchi and E. Cherchi, "Electric vehicle forecasts: a review of models and methods including diffusion and substitution effects," *Transport Reviews*, vol. 43, pp. 1118–1143, 2023.

[80] A. Charly and B. Caulfield, "Transport emission modelling based on a bottom-up approach to facilitate sustainable transport planning," *Sustainable Futures*, vol. 9, 2025.

[81] M. S. Alam and P. Duffy, "Improvement in the estimation and back-extrapolation of co2 emissions from the irish road transport sector using a bottom-up data modelling approach," *Transportation Research Part D: Transport and Environment*, vol. 56, pp. 18–32, 2017.

[82] H. Zhang, X. Yin, and W. Chen, "A bottom-up model analysis of transport sector: a study of china and usa," *Energy Procedia*, vol. 61, pp. 895–898, 2014.

[83] C. Brand, G. Marsden, J. I. Anable, J. Dixon, and J. Barrett, "Achieving deep transport energy demand reductions in the united kingdom," *Renewable and Sustainable Energy Reviews*, vol. 207, 2025.

[84] C. Brand. Uk transport carbon model: reference guide. [Online]. Available: https://ukerc.ac.uk/publications/uk-transport-carbon-model-reference-guide/

[85] T. E. Worseley and R. C. E. Harris, *National Transport Models.* Springer, 2002, ch. General Modelling Approaches: Top-down or Bottom-up?

[86] S. Jones and L. Garcia. What is agent-based modelling and how can it be useful for public health research? [Online]. Available: https://www.ncrm.ac.uk/news/show.php?article=5824

[87] M. Klein, L. Lupke, and M. Gunther, "Home charging and electric vehicle diffusion: Agent-based simulation using choice-based conjoint data," *Transportation Research Part D: Transport and Environment*, vol. 88, 2020.

[88] H. Dia, "An agent-based approach to modelling driver route choice behaviour under the influence of real-time information," *Transportation Research Part C: Emerging Technologies*, vol. 10, pp. 331–349, 2002.

[89] Columbia Mailman School of Public Health. Agent-based modelling. [Online]. Available: https://www.publichealth.columbia.edu/research/population-health-methods/agent-based-modeling

[90] A. Turrell. Agent-based models: understanding the economy from the bottom up. [Online]. Available: https://www.bankofengland.co.uk/-/media/boe/files/quarterly-bulletin/2016/agent-based-models-understanding-the-economy-from-the-bottom-up.pdf

[91] F. S. Hoen, M. Diez-Gutierrez, S. Babri, S. Hess, and T. Torset, "Charging electric vehicles on long trips and the willingness to pay to reduce waiting for charging. stated preference survey in norway," *Transportation Research Part A: Policy and Practice*, vol. 175, no. 103774, 2023.

[92] L. Sica, A. Carboni, F. Deflorio, and C. Botta, "Electric vehicle recharging options in urban areas: Discrete choice modeling to estimate user preference," *Sustainable Cities and Society*, vol. 121, 2025.

[93] I. Kristoffersson, R. Pyddoke, F. Kristofersson, and S. Algers, "Access to charging infrastructure and the propensity to buy an electric car," *Transportation Research Part D: Transport and Environment*, vol. 139, 2025.

[94] C. G. Prato, "Route choice modeling: past, present and future research directions," *Journal of Choice Modelling*, vol. 2, pp. 65–100, 2009.

[95] Centre for International Economics. Review of willingness-to-pay methodologies. [Online]. Available: https://www.ipart.nsw.gov.au/sites/default/files/

documents/report_-_review_of_willingness_to_pay_methodologies_-_centre_for_international_economics_-_ross_chapman_-_august_2001_-_pdf_version.pdf

[96] L. M. Hunt, *Monitoring, Simulation and Management of Visitor Landscapes*. The University of Arizona Press, 2008, ch. Chapter 11 - Choice Models: Estimation, evolution, limitations and potential application for simulation modelling.

[97] A. deWaal and J. W. Joubert, "Explainable bayesian networks applied to transport vulnerability," *Expert Systems with Applications*, vol. 209, 2022.

[98] J. W. Joubert and A. de Waal, "Activity-based travel demand generation using bayesian networks," *Transportation Research Part C: Emerging Technologies*, vol. 120, 2020.

[99] J. L. Puga, M. Krzywinski, and N. Altman, "Bayesian networks," *Nature Methods*, vol. 12, pp. 799–800, 2015.

[100] Stanford Encyclopedia of Philosophy. Bayes' theorem. [Online]. Available: https://plato.stanford.edu/entries/bayes-theorem/

[101] S. Nadkarni and P. P. Shenoy, "A bayesian network approach to making inferences in causal maps," *European Journal of Operational Research*, vol. 128, pp. 479–498, 2001.

[102] K. Sedki and L. B. de Beaufort, "Cognitive maps and bayesian networks for knowledge representation and reasoning," in *IEEE 24th International Conference on Tools with Artificial Intelligence*, 2012.

[103] S. Nadkarni and P. P. Shenoy, "A causal mapping approach to constructing bayesian networks," *Decision Support Systems*, vol. 38, pp. 259–281, 2001.

[104] Y. Y. Wee, W. P. Cheah, S. C. Tan, and K. Wee, "An evaluation of the role of fuzzy cognitive maps and bayesian belief networks in the development of causal knowledge systems," *Journal of Intelligent and Fuzzy Systems*, vol. 37, pp. 1905–1920, 2019.

[105] A. L. P. Rodrigues, P. Wells, L. Cipcigan, and S. R. da Cal Seixas, "Forecasting the costs of battery electric buses: A system dynamics model perspective," *Research in Transportation Business Management*, vol. 57, 2024.

[106] A. L. P. Rodrigues, L. Cipcigan, D. Potoglou, D. Dattero, P. Wells, and S. R. da Cal Seixas, "Impacts of subsidy efficiency on bus electrification: A participatory system dynamic modelling," *Transport Policy*, vol. 167, pp. 210–221, 2025.

[107] S. P. Shepherd, "A review of system dynamics models applied in transportation," *Transportmetrica B: Transport Dynamics*, vol. 2, no. 2, pp. 83–105, 2014.

[108] D. N. Ford, "A system dynamics glossary," *System Dynamics Review*, vol. 35, no. 4, pp. 369–379, 2019.

[109] M. Zomorodian, A. H. Lai, M. Homayounfar, S. Ibrahim, S. E. Fatemi, and A. El-Shafie, "The state-of-the-art system dynamics application in integrated water resources modeling," *Journal of Environmental Management*, vol. 227, pp. 294–304, 2018.

[110] Sustainability Directory. What are the limitations of system dynamics approach? [Online]. Available: https://pollution.sustainability-directory.com/question/what-are-the-limitations-of-system-dynamics-approach/

[111] W. Zhang, M. Zhang, and G. Wu, "How to realize low-carbon travel in rural areas? evidence from china," *Transportation Research Part D: Transport and Environment*, vol. 105, no. 103224, 2022.

[112] N. Ghaffarzadegan, J. Lyneis, and G. P. Richardson, "How small system dynamics models can help thepublic policy process," *System Dynamics Review*, vol. 27, pp. 22–44, 2010.

[113] H. B. Martensson, K. Larsen, and M. Hojer, "Investigating potential effects of mobility and accessibility services using the avoid-shift-improve framework," *Sustainable Cities and Society*, vol. 96, no. 104676, 2023.

[114] A. Eisenkopf and C. Burgdorf, "Policy measures and their impact on transport performance, modal split and greenhouse gas emissions in german long-distance passenger transport," *Transportation Research Interdisciplinary Perspectives*, vol. 14, no. 100615, 2022.

[115] R. F. Nassar, V. Ghisolfi, J. A. Annema, A. v. Binsbergen, and L. A. Tavasszy, "A system dynamics model for analyzing modal shift policies towards decarbonization in freight transportation," *Research in Transportation Business Management*, vol. 48, no. 100966, 2023.

[116] L. Wen and A. Wang, "System dynamics model of beijing urban public transport carbon emissions based on carbon neutrality target," *Environment, Development and Sustainability*, vol. 25, pp. 12 681–12 706, 2023.

[117] B. Makwana. Rac foundation electric vehicle charging in scotland. [Online]. Available: https://www.racfoundation.org/assets/rac_foundation/content/downloadables/Scotland_EV_Network_Final_Makwana_Feb_2015.pdf

[118] ——. Rac foundation electric vehicle charge point usage in scotland – august 2015 and 2016 update. [Online]. Available: https://www.racfoundation.org/wp-content/uploads/2017/11/Scotland_EV_Network_Makwana_Nov_16.pdf

[119] S. I. Bayram, A. Saad, R. Sims, A. Babu, C. Edmunds, and S. Galloway, "Statistical characterisation of public ac ev chargers in the uk," *IEEE Access*, vol. 4, 2016.

[120] A. Almaghrebi, S. Shom, F. A. Juheshi, K. James, and M. Alahmad, "Analysis of user charging behavior at public charging stations," in *IEEE Transportation Electrification Conference and Expo (ITEC)*, Detroit, Michigan, 2019.

[121] B. Borlaug, F. Yang, E. Pritchard, E. Wood, and J. Gonder, "Public electric vehicle charging station utilisation in the united states," *Transportation Research Part D: Transport and Environment*, vol. 114, no. 103564, 2023.

[122] J. Francfort. What use patterns were observed for plug-in electric vehicle drivers at publicly accessible alternating current level 2 electric vehicle supply equipment sites? [Online]. Available: https://inldigitallibrary.inl.gov/sites/sti/sti/6899530.pdf

[123] B. J. Mortimer, A. D. Bach, C. Hecht, D. U. Sauer, and R. W. D. Doncker, “Public charging infrastructure in germany – a utilization and profitability analysis,” *Journal of Modern Power Systems and Clean Energy*, vol. 10, no. 6, pp. 1750–1760, 2022.

[124] R. Wolbertus, R. v. d. Hoed, and S. Maase, “Benchmarking charging infrastructure utilization,” *World Electric Vehicle Journal*, vol. 8, no. 4, pp. 754–771, 2016.

[125] R. Wolbertus, M. Kroesen, R. v. d. Hoed, and C. Chorus, “Fully charged: An empirical study into the factors that influence connection times at ev-charging stations,” *Energy Policy*, vol. 123, pp. 1–7, 2018.

[126] P. Morrissey, P. Weldon, and M. O’Mahony, “Future standard and fast charging infrastructure planning: An analysis of electric vehicle charging behaviour,” *Energy Policy*, vol. 89, pp. 257–270, 2016.

[127] M. Akil, E. Kilic, R. Bayindir, A. Sebati, and R. Malek, “Uncoordinated charging profile of evs based on an actual charging session data,” in *10th IEEE International Conference on Renewable Energy Research and Applications*, Istanbul, Turkey, 2021.

[128] T.-Y. Ma and S. Faye, “Multistep electric vehicle charging station occupancy prediction using hybrid lstm neural networks,” *Energy*, vol. 244, no. 123217, 2022.

[129] A. Orzechowski, L. Lugosch, H. Shu, R. Yang, and W. Li, “A data-driven framework for medium-term electric vehicle charging demand forecasting,” *Energy and AI*, vol. 14, no. 100267, 2023.

[130] A. H. Golsefidi, F. B. Hüttel, I. Peled, S. Samaranayake, and F. C. Pereira, "A joint machine learning and optimization approach for incremental expansion of electric vehicle charging infrastructure," *Transportation Research Part A: Policy and Practice*, vol. 178, no. 103863, 2023.

[131] ChargePlace Scotland. Monthly charge point performance. [Online]. Available: https://chargeplacescotland.org/monthly-charge-point-performance/

[132] S. LaMonaca and L. Ryan, "The state of play in electric vehicle charging services – a review of infrastructure provision, players, and policies," *Renewable and Sustainable Energy Reviews*, vol. 154, no. 111733, 2022.

[133] International Energy Agency. Global ev outlook 2024: Trends in electric vehicle charging. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-vehicle-charging

[134] GridX. European ev charging report 2024. [Online]. Available: https://www.gridx.ai/resources/european-ev-charging-report-2024

[135] International Energy Agency. Global ev outlook 2021: Trends and developments in electric vehicle markets. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2021/trends-and-developments-in-electric-vehicle-markets

[136] Improvement Service Spatial Hub. Local authority boundaries - scotland. [Online]. Available: https://data.spatialhub.scot/dataset/local_authority_boundaries-is

[137] East Ayrshire Council. Electric vehicle charging tariffs to be introduced in east ayrshire from 1 april. [Online]. Available: https://newsroom.east-ayrshire.gov.uk/news/electric-vehicle-charging-tariffs-to-be-introduced-in-east-ayrshire-from-1-april

[138] South Ayrshire Council. Ayrshire's new public ev charging tariff. [Online]. Available: https://www.south-ayrshire.gov.uk/article/61111/Ayrshire-s-new-public-EV-charging-tariff

[139] East Lothian Council. New off-peak charge tariffs for evs. [Online]. Available: https://www.eastlothian.gov.uk/news/article/13999/drivers_encouraged_to_charge_off-peak

[140] Scottish Futures Trust. Electric vehicle infrastructure fund (evif): Frequently asked questions. [Online]. Available: https://www.scottishfuturestrust.org.uk/publications/documents/frequently-asked-questions-june-2023

[141] Scottish Government. Scottish index of multiple deprivation 2020. [Online]. Available: https://simd.scot/#/simd2020/BTTTFTT/12.740929652757556/-4.1798/55.8498/

[142] ——. Scottish government urban rural classification 2020. [Online]. Available: https://www.gov.scot/publications/scottish-government-urban-rural-classification-2020/pages/2/

[143] Office for National Statistics. Simd 2020 technical notes. [Online]. Available: https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2020/09/simd-2020-technical-notes/documents/simd-2020-technical-notes/simd-2020-technical-notes/govscot%3Adocument/SIMD%2B2020%2Btechnical%2Bnotes.pdf

[144] L. Philip, R. Wilson, and P. Duffy, "Rurality, islandness and public policy in scotland," *Scottish Geographical Journal*, vol. 140, no. 1–2, pp. 113–135, 2022.

[145] Transport Scotland. Transport and travel in scotland 2022. [Online]. Available: https://www.transport.gov.scot/publication/transport-and-travel-in-scotland-2022/

[146] ——. Plan to add 24,000 public electric vehicle charge points by 2030 published. [Online]. Available: https://www.transport.gov.scot/news/plan-to-add-24-000-public-electric-vehicle-charge-points-by-2030-published/

[147] M. Nicholas and N. Lutsey, "Quantifying the electric vehicle charging infrastructure gap in the united kingdom," *International Council on Clean Transportation*, 2020.

[148] A. Thingvad, P. B. Andersen, T. Unterluggauer, C. Træholt, and M. Marinelli, "Electrification of personal vehicle travels in cities - quantifying the public charging demand," *eTransportation*, vol. 9, no. 100125, 2021.

[149] Scottish Government. Building regulations - energy standards and associated topics - proposed changes: consultation. [Online]. Available: https://www.gov.scot/publications/scottish-building-regulations-proposed-changes-energy-standards-associated-topics/pages/7/

[150] S. I. Bayram, U. Zafar, and S. Bayhan, "Could petrol stations play a key role in transportation electrification? a gis-based coverage maximization of fast ev chargers in urban environment," *IEEE Access*, vol. 10, pp. 17 318–17 329, 2022.

[151] P. Prakobkaew and S. Sirsumrannukul, "Optimal locating and sizing of charging stations for large-scale areas based on gis data and grid partitioning," *Transmission Distribution*, vol. 18, pp. 1235–1254, 2024.

[152] B. Vansola, M. Chandra, and R. N. Shukla, "Gis-based model for optimum location of electric vehicle charging stations," *Recent Advances in Transportation Systems Engineering and Management, Lecture Notes in Civil Engineering*, vol. 261, 2023.

[153] H. Iravani, "A multicriteria gis-based decision-making approach for locating electric vehicle charging stations," *Transportation Engineering*, vol. 9, 2022.

[154] A. Patil, A. Giriyappanavar, B. Vaidya, and H. T. Mouftah, "Site suitability assessment of public ev charging stations in urban environment," in *IEEE Canadian Conference on Electrical and Computer Engineering (CCECE)*, Halifax Nova Scotia, Canada, 2022.

[155] M. Kazempour, H. Sabboubeh, K. P. Moftakhari, R. Najafi, and G. Fusco, "Gis-based geospatial analysis for identifying optimal locations of residential on-street electric vehicle charging points in birmingham, uk," *Sustainable Cities and Society*, vol. 120, no. 105988, 2025.

[156] A. Charly, N. J. Thomas, A. Foley, and B. Caulfield, "Identifying optimal locations for community electric vehicle charging," *Sustainable Cities and Society*, vol. 94, no. 104573, 2023.

[157] ArcGIS Pro Esri. Why hexagons? [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-statistics/h-whyhexagons.htm

[158] Irish Government. Why your journey counts. [Online]. Available: https://www.gov.ie/en/publication/004a9-your-journey-counts/

[159] Simantics. Simantics system dynamics. [Online]. Available: http://sysdyn.simantics.org/

[160] Transport Scotland. Scottish transport statistics 2021. [Online]. Available: https://www.transport.gov.scot/publication/scottish-transport-statistics-2021/

[161] KPMG. Trends in scottish bus patronage. [Online]. Available: https://www.cpt-uk.org/media/b3rgvsvx/trends-in-bus-use-in-scotland-final-20240904.pdf

[162] UK Government. Greenhouse gas reporting: conversion factors 2023. [Online]. Available: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023

[163] G. Davis. Technical paper — your new electric car emits 75 gco2/km (at the power station). [Online]. Available: https://ecometrica.com/assets/electric_car_emits_75_gCO2_per_km.pdf

[164] United States Department of Transportation. Zero-emission bus evaluation results: King county metro battery electric buses (report 00118). [Online]. Available: https://www.transit.dot.gov/research-innovation/zero-emission-bus-evaluation-results-king-county-metro-battery-electric-buses

[165] MathWorks. Matlab. [Online]. Available: https://uk.mathworks.com/products/matlab.html

[166] Transport Scotland. Scottish transport statistics 2021 transport environment. [Online]. Available: https://www.transport.gov.scot/media/51297/chapter-13-environment-scottish-transport-statistics-2021.pdf

[167] Office for National Statistics. Regional gross domestic product: all itl regions. [Online]. Available: https://www.ons.gov.uk/economy/grossdomesticproductgdp/datasets/regionalgrossdomesticproductallnutslevelregions

[168] ——. Estimates of the population for the uk, england, wales, scotland and northern ireland. [Online]. Available: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/populationestimatesforukenglandandwalesscotlandandnorthernireland

[169] T. Howgego, K. Orchard, and R. Riley. The future of the bus vehicle market in scotland. [Online]. Available: https://www.climatexchange.org.uk/media/5573/cxc-the-future-of-the-bus-vehicle-market-in-scotland-december-2022.pdf

[170] National Records of Scotland. Scotland's census first results. [Online]. Available: https://www.nrscotland.gov.uk/news/2023/scotland%E2%80%99s-census-first-results

[171] Scottish Government. Gdp quarterly national accounts, scotland. [Online]. Available: https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2023/04/gdp-quarterly-national-accounts-2022-q4/documents/gdp-quarterly-national-accounts-full-publication/gdp-quarterly-national-accounts-full-publication/govscot%3Adocument/

[172] National Records of Scotland. Projected population of scotland (2020-based). [Online]. Available: https://www.nrscotland.gov.uk/statistics-and-data/statistics/statistics-by-theme/population/population-projections/population-projections-scotland/2020-based/2020-based-unrevised

[173] Scottish Fiscal Commission. Scotland's economic and fiscal forecasts – may 2023. [Online]. Available: https://www.fiscalcommission.scot/publications/scotlands-economic-and-fiscal-forecasts-may-2023/

[174] C. Goodall, *How to live a low-carbon life.* Earthscan, 2007, ch. Public Transport.

[175] Transport Scotland. Transport and travel in scotland 2021: Results from the scottish household survey. [Online]. Available: https://www.transport.gov.scot/publication/transport-and-travel-in-scotland-2021-results-from-the-scottish-household-survey/

[176] ——. Carbon account for transport no. 12: 2020 edition. [Online]. Available: https://www.transport.gov.scot/publication/carbon-account-for-transport-no-12-2020-edition/

[177] M. Mehdizadeh, M. F. Zavareh, and T. Nordfjaern, "Mono- and multimodal green transport use on university trips during winter and summer: Hybrid choice models on the norm-activation theory," *Transportation Research Part A: Policy and Practice*, vol. 130, pp. 317–332, 2019.

[178] J. Angarita-Zapata and H. Andrade-Sosa, "Structural policies to address induced travel demand by road construction," in *Proceedings of the 34th International Conference of the System Dynamics Society*, Delft, Netherlands, 2016.

[179] Electric Vehicle Database. Useable battery capacity of electric vehicles. [Online]. Available: https://ev-database.org/uk/cheatsheet/useable-battery-capacity-electric-car

[180] ChargePlace Scotland. Charge point tariffs. [Online]. Available: https://chargeplacescotland.org/charge-point-tariffs/

[181] Esri. Resources for arcmap. [Online]. Available: https://www.esri.com/en-us/arcgis/products/arcgis-desktop/resources

[182] ——. Spatial join (analysis). [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/tool-reference/analysis/spatial-join.htm

[183] Scottish Government. Simd rank to quintile, decile, and vigintile. [Online]. Available: https://www.gov.scot/publications/simd-rank-to-quintile-decile-and-vigintile/

[184] Y. Dodge, *The Concise Encyclopedia of Statistics.* Springer, 2008, ch. Kolmogorov–Smirnov Test.

[185] Esri. Geoplan postcode data. [Online]. Available: https://hub.arcgis.com/pages/fdf7e193eb5043efb7d3d6bba8535f28

[186] Office for National Statistics. Postal geographies. [Online]. Available: https://www.ons.gov.uk/methodology/geography/ukgeographies/postalgeography

[187] Scottish Government. Scottish index of multiple deprivation 2020: introduction; how can i use simd? [Online]. Available: https://www.gov.scot/publications/scottish-index-multiple-deprivation-2020/pages/4/

[188] C. M. Fischbacher. Identifying "deprived individuals": are there better alternatives to the scottish index of multiple deprivation (simd) for socioeconomic targeting in individually based programmes addressing health inequalities in scotland? [Online]. Available: https://www.scotpho.org.uk/media/1166/scotpho140109-simd-identifyingdeprivedindividuals.pdf

[189] J. Thomson. Simd rural deprivation: Evidence summary. [Online]. Available: https://www.gov.scot/binaries/content/documents/govscot/publications/research-and-analysis/2017/02/scottish-index-of-multiple-deprivation-rural-deprivation-evidence-and-case-studies/documents/rural-deprivation-an-evidence-review/rural-deprivation-an-evide

[190] National Records of Scotland. Population estimates by urban rural classification (2011 data zone based). [Online]. Available: https://www.nrscotland.gov.uk/statistics-and-data/statistics/statistics-by-theme/population/population-estimates/2011-based-special-area-population-estimates/population-estimates-by-urban-rural-classification

[191] Fraser of Allander Institute. Dramatic stagnation to improvements in living standards affecting scotland's health. [Online]. Available: https://fraserofallander.org/dramatic-stagnation-to-improvements-in-living-standards-affecting-scotlands-health/

[192] D. Finch, H. Wilson, and J. Bibby. Leave no one behind: The state of health and health inequalities in scotland. [Online]. Available: https://www.health.org.uk/reports-and-analysis/reports/leave-no-one-behind

[193] Transport Scotland. The draft implementation plan: Integrated impact assessments. [Online]. Available: https://www.transport.gov.scot/publication/the-draft-implementation-plan-integrated-impact-assessments-1/baseline/

[194] Scottish Government. Scottish islands: data overview 2023. [Online]. Available: https://www.gov.scot/publications/scottish-islands-data-overview-2023/pages/5/

[195] National Records of Scotland. Table 9: Land area and population density by administrative area, mid-2017. [Online]. Available: https://web.archive.org/web/20190608025833/https://www.nrscotland.gov.uk/files/statistics/populationestimates/mid-17/tables/mid-year-pop-est-17-tab-9.pdf

[196] UK Government. Seasonal variations in electricity demand. [Online]. Available: https://assets.publishing.service.gov.uk/media/5a7ba36540f0b645ba3c59b2/Seasonal_variations_in_electricity_demand.pdf

[197] ChargePlace Scotland. Clackmannanshire council. [Online]. Available: https://chargeplacescotland.org/clackmannanshire-council/

[198] East Dunbartonshire Council. Electronic vehicle charging – tariffs to be introduced in east dunbartonshire. [Online]. Available: https://www.eastdunbarton.gov.uk/news/2023/september-2023/electronic-vehicle-charging-tariffs-to-beintroduced-in-east-dunbartonshire/

[199] East Renfrewshire Council. Electric vehicle charging tariffs to be introduced in east renfrewshire. [Online]. Available: https://www.eastrenfrewshire.gov.uk/article/6101/Electric-vehicle-charging-tariffs-to-be-introduced-in-EastRenfrewshire

[200] Glasgow City Council. Electric vehicle charging. [Online]. Available: https://www.glasgow.gov.uk/article/2393/Electric-Vehicle-Charging

[201] North Lanarkshire Council. Tariffs to be introduced for public ev chargers. [Online]. Available: https://www.northlanarkshire.gov.uk/news/tariffs-be-introduced-public-ev-chargers

[202] Perth and Kinross Council. Introduction of charging for electric vehicles. [Online]. Available: https://perthand-kinross.cmis.uk.com/perth-and-kinross/Document.ashx?czJKcaeAi5tUFL1DTL2UE4zNRBcoShgo=mr85pgBMoOLby2wgRtez3mA65lzmRvdZA/L4Vmk/lOWt4bw+F6hywA==&rUzwRPf+Z3zd4E7Ikn8Lyw===pwRE6AGJFLDNlh225F5QMaQWCtPHwdhUfCZ/LUQzgA2uL5jNRG4jdQ==&mCTIbCubSFfXsDGW9IXnlg===hFflUdN3100=&kCx1AnS9/pWZQ40DXFvdEw===hFflUdN3100=&uJovDxwdjMPoYv+AJvYtyA===ctNJFf55vVA=&FgPlIEJYlotS+YGoBi5olA===NHdURQburHA=&d9Qjj0ag1Pd993jsyOJqFvmyB7X0CSQK=ctNJFf55vVA=&WGewmoAfeNR9xqBux0r1Q8Za60lavYmz=ctNJFf55vVA=&WGewmoAfeNQ16B2MHuCpMRKZMwaG1PaO=ctNJFf55vVA=

[203] ChargePlace Scotland. 1st april tariff update. [Online]. Available: https://chargeplacescotland.org/tariff/1st-april-tariff-update/

[204] Shetland Islands Council. Electric vehicle charging tariffs from 11th april 2023. [Online]. Available: https://www.shetland.gov.uk/news/article/2496/electric-vehicle-charging-tariffs-from-11th-april-2023

[205] South Lanarkshire Council. Electric vehicle charging. [Online]. Available: https://www.southlanarkshire.gov.uk/info/200229/parking_and_car_parks/2003/electric_vehicle_charging/2

[206] Stirling Council. Electric vehicle charging tariff to be introduced to support demand. [Online]. Available: https://www.stirling.gov.uk/news/electric-vehicle-charging-tariff-to-be-introduced-to-support-demand/

[207] West Dunbartonshire Council. New electric charging tariff to be introduced in west dunbartonshire. [Online]. Available: https://www.west-dunbarton.gov.uk/council/newsroom/news/2023/may/electric-charging-tariff/

[208] West Lothian Council. New electric car vehicle charging tariffs now in place. [Online]. Available: https://www.westlothian.gov.uk/article/77133/New-electric-car-vehicle-charging-tariffs-now-in-place

[209] M. de Haas, M. Terwindt, and J.-J. Witte, "Pricing tools: better as a package? how pricing and other tools influence the choice for public transport," *Netherlands Institute for Transport Policy Analysis KiM and Ministry of Infrastructure and Water Management*, 2023.

[210] Zapmap. Ev charging statistics 2025. [Online]. Available: https://www.zap-map.com/ev-stats/how-many-charging-points

[211] Esri. Arcgis pro. [Online]. Available: https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview

[212] National Records of Scotland. 2022 census geography products 2024. [Online]. Available: https://www.nrscotland.gov.uk/publications/2022-census-geography-products/

[213] EVA England. The great ev charging report. [Online]. Available: https://www.evaengland.org.uk/wp-content/uploads/2023/12/EVAE-the-great-ev-charging-report.pdf

[214] Consumer Scotland. Consumer experience of electric vehicles in scotland (html). [Online]. Available: https://consumer.scot/publications/consumer-experience-of-electric-vehicles-in-scotland-html/

[215] UK Government. National travel survey. [Online]. Available: https://www.gov.uk/government/collections/national-travel-survey-statistics