ANALYSIS OF ELECTRIC VEHICLE USER RECHARGING BEHAVIOUR AND THE EFFECTIVENESS OF USING FINANCIAL INCENTIVES TO MANAGE RECHARGING DEMAND

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Abstract

An anticipated increase in the number of electric vehicles (EVs) on the road has created the need to understand and manage recharging demand in order to prevent localised overloading of power distribution networks during peak hours. Smart meters at home, in conjunction with off-peak energy tariffs, have been proposed as a demand management tool. This has not been tested in a region with a high density recharging infrastructure whereby drivers pay an annual fixed fee for unlimited use of non-domestic recharging infrastructure networks. This research quantified daily recharging demand profiles and assessed the effectiveness of incentivising off-peak recharging in such a region. The North East of England was used as the study area. Between 2010 and 2013, 401 home, 312 workplace and 412 public non-domestic recharging posts were installed. Recharging data were available from SwitchEV; a three year, real world EV deployment study that commenced in 2010. Sources of data were in-vehicle loggers, focus groups and questionnaires. There were 23 Private, 43 Organisation Individual users and 74 Organisation Pool users in total. Five statistically significantly different representative recharging profiles were identified. None of these profiles had high demand peaks during the off-peak hours between midnight and 07:00hrs. Interventions took place for 21 users. A 50% reimbursement for off-peak recharging was offered. At home, off-peak recharging increased by 23%. No significant changes in recharging behaviour occurred at any other recharging location. There was also no statistically significant change in the proportion of total recharging recorded at each location. Focus groups and questionnaires revealed the common theme of drivers using EV recharging posts as they offer free and convenient parking bays, rather than out of a need to recharge the battery in order to complete an upcoming trip. Furthermore, the absence of timing devices and organisation policy dictating that EVs must be recharged immediately upon returning to the premises limited the ability of organisations to deliver behavioural change. It is recommended that pay-as-you-go access to non-domestic recharging infrastructure be implemented to reduce unnecessary daytime recharging and that workplace recharging infrastructure is fitted with smart meters. These changes are required as this research has highlighted limitations of the current proposed policy.

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Contents

List of Figures viii

List of Tables.......... xiv

Abbreviations xviii

1. Introduction..........1
   - 1.1. Research Background 1
   - 1.2. Research Questions 5
   - 1.3. Aim and Objectives..........5
   - 1.4. Scope of Research 6
   - 1.5. Thesis Structure..........6
2. Literature Review 8
   - 2.1. Introduction..........8
   - 2.2. Policy Evolution 9
   - 2.3. EV Early Adopters, Purchase Incentives and Future Market Trends ...12
   - 2.4. EV Recharging Infrastructure..........15
     - 2.4.1. European Union 15
     - 2.4.2. UK Government Plans for EV Recharging Infrastructure 16
     - 2.4.3. UK Plugged-in-Places Programme..........17
     - 2.4.4. Plugged-in-Places in the North East of England 18
     - 2.4.5. EV Recharging Infrastructure Policy and Installation in the United States and China..........22
   - 2.5. Impact of EV Recharging Demand on Power Distribution Networks....23
     - 2.5.1. Impact of Additional Loads on Power Distribution Networks 24
     - 2.5.2. Carbon Content of Electricity Used to Recharge EVs 27
   - 2.6. Power Generation and Demand in the UK..........28
   - 2.7. UK Carbon Content of Electricity Generation..........30
     - 2.7.1. Definitions of the Carbon Content of a Unit of Electricity..........31
     - 2.7.2. Methods of Calculating the Carbon Emissions Factor..........32
   - 2.8. Theoretical EV Driver Behaviour and Recharging Demand Profiles 33
   - 2.9. Review of Real World Recharging Data..........36
     - 2.9.1. CENEX Smart Move Trials..........36
     - 2.9.2. UK Ultra Low Carbon Vehicle Demonstrator Trials 36
     - 2.9.3. Coventry and Birmingham Low Emission Vehicle Demonstrator (CABLED)..........39

2.9.4. BMW MINI E 40
2.9.5. SwitchEV Trials 41
2.9.6. EV Recharging Infrastructure Data..42
2.10. Financial Incentives and Intervention Design 43
2.10.1. Financial Incentives...44
2.10.2. Delivery of Information 45
2.10.3. Impact of Users' Perceived Difficulty of Behavioural Change on Intervention Results..47
2.10.4. Use of Feedback and Goal Setting..47
2.10.5. Impact of Attitudes towards Climate Change and the Environment 48
2.11. Review of Statistical Methods for Data Clustering 49
2.11.1. Methodological Approaches to Data Clustering 50
2.11.2. Defining the Distance between Objects...51
2.11.3. Identifying the Number of Clusters within the Dataset...........................51
2.12. Identification of Key Themes from Focus Group Discussion and Written Driver Responses..52
2.12.1. Review of Methods of Focus Group Analysis..52
2.12.2. Themes and Sub-Themes..54
2.12.3. Inductive and Deductive Approaches to Theme Identification.......................55
2.12.4. Quantitative Analysis of Themes..55
2.13. Literature Review Summary 56
3. Methodology...59
3.1. Introduction..59
3.2. Methodology Part One: SwitchEV Consortium 62
3.2.1. Introduction 62
3.2.2. Study Area and Installation of EV Recharging Infrastructure 63
3.2.3. Driver Recruitment and Trial Management...63
3.2.4. Hard Data Collection and Processing...65
3.2.5. Soft Data Collection...68
3.3. Data Processing and Identification of Typical Recharging Profiles......................70
3.3.1. Identification of Recharging Profiles..70
3.3.2. Calculating the Carbon Content of Electricity Associated with EV Recharging..71
3.3.3. Cluster Analysis..74

3.3.4. Analysis of Cluster Allocation 75
3.3.5. Further Analysis of Driver Behaviour within Clusters 76
3.4. Design, Implementation and Analysis of the Intervention Process 76
3.4.1. Incentives and Driver Recruitment 76
3.4.2. Selection of Control Group 78
3.4.3. Analysis of Interventions 79
3.4.4. Assessment of Behavioural Change 83
3.4.5. Testing the Relationship Between Response to Intervention and Total User Recharging duration 84
3.4.6. Feedback from Intervention Participants 84
3.5. Analysis of Focus Group Transcripts and Written Driver Responses 86
3.6. Summary of Methodology Chapter 87
4. User Recruitment, Data Collection and Soft Data Analysis 89
4.1. Introduction 89
4.2. Review of SwitchEV Participants 89
4.2.1. User Types Taking Part in SwitchEV 89
4.1. SwitchEV User Demographics 91
4.2. Summary of Data Collected 95
4.3. Thematic Analysis Results 99
4.3.1. Key Themes Identified 99
4.3.2. Review of Theme One – Recharging Habits 100
4.3.3. Review of Theme Two – Circumstantial Need to Recharge 101
4.3.4. Review of Theme Three – Influence of North East NE PiP 103
4.4. Post-Trial Online Questionnaire Responses 105
4.5. Summary of Key Findings 107
5. Derivation and Analysis of Recharging Profiles 110
5.1. Introduction 110
5.2. Defining the Pre-Intervention Period for Control Group Users 111
5.3. Identification of Clusters within the Pre-Intervention Recharging Data 111
5.3.1. Number of Clusters 111
5.3.2. Overall Recharging Demand Profiles for Four, Five and Six Cluster Solutions 112
5.4. Analysis of the Five Cluster Recharging Profiles Solution 115
5.4.1. Recharging Profile Allocation by User Type 116

5.4.2. Overall Duration of Recharging by Location 118
5.5. Large Morning Recharging Profile 120
5.6. Small Morning Recharging Profile 122
5.7. End of Working Day Recharging Profile..127
5.8. Early Evening Recharging Profile 128
5.9. Late Evening Recharging Profile 133
5.10. Comparison of Recharging Demand Profiles by Location 137
5.11. Summary of Key Findings from Recharging Profile Analysis..........142
6. Analysis of User Interventions 144
6.1. Introduction 144
6.2. Intervention Participants 145
6.3. Selection of Control Group...146
6.4. Control Group Analysis 150
6.4.1. Overall Percentage Difference in Off-Peak Recharging before and after the Intervention Period 150
6.4.2. Difference between Recharging Infrastructure Usage before and after the Intervention Period 155
6.4.3. Difference in Off-Peak Recharging by Post-Intervention Month ..158
6.4.4. Quantifying the Differences in Control Group Carbon Content of Electricity during EV Recharging during Pre and Post-Intervention Time Periods... 160
6.4.5. Impact of Control Group Results on Intervention Analysis 163
6.5. Intervention Participant Results 164
6.5.1. Overall Changes in Frequency of Off-Peak Recharging.............164
6.5.2. Changes in Frequency of Off-Peak Recharging by Location.......164
6.5.3. Analysis of Changes in Frequency of Recharging Infrastructure Usage for Users taking part in Interventions...168
6.5.4. Analysis of Month by Month Changes in Off-Peak Recharging Behaviour 173
6.5.5. Carbon Content of Electricity during EV Recharging for Intervention Participants...174
6.5.6. Further Analysis of Home Recharging Behaviour for Drivers Participating in Intervention Scheme 177
6.5.7. Impact of Total Recharging Duration on Intervention Success....179
6.5.8. Change in total hourly recharging frequency...............................180
6.5.9. Intervention Participant Responses to Questionnaire..................181

6.5.10. Critique 185

6.6. Summary of Key Findings from the Intervention Analysis 185

7. Conclusions and Recommendations 187

7.1. Introduction 187

7.2. Users Recruited and Data Collected from SwitchEV 188

7.3. Analysis of Driver Recharging Profiles Observed during Pre-Intervention Stage of Trials 189

7.4. Conclusions from User Interventions 194

7.5. Key Recommendations Arising from the Findings of this Research .. 197

7.6. Limitations of this research and discussion of methodological approach 199

7.7. Recommendations for Future Work 202

8. References 204

9. Research Dissemination 216

9.1. Journal Publication 216

9.2. Conference Papers 216

9.3. Awards 216

List of Figures

Figure 2-1: UK Plugged-in-Places regions (Office for Low Emission Vehicles, 2011) 18

Figure 2-2: Cumulative number of recharging units installed in the NE PiP network (Charge Your Car, 2013) 20

Figure 2-3: Location of NE PiP network within the UK (above) and (below) recharging post locations within the region (pink circles) 21

Figure 2-4: Electricity generation capacity in the UK by power sources (National Grid, 2011b) 28

Figure 2-5: Power generation sources used in the UK on a typical winter day (top) and summer day (bottom) to meet electricity demand (National Grid, 2011a) 29

Figure 2-6: Comparison of theoretical recharging demand profiles defined in literature by different researchers 35

Figure 2-7: Frequency of the start time of recharging events by user types from the first year of the ULCVD trials (Everett et al., 2011) 38

Figure 2-8: EV Recharging profiles by hour of day (left) and demand by location (right) in the CABLED project (Bruce et al., 2012) 39

Figure 2-9: Recharging demand profile at home for UK MINI E trial participants (BMW Group, 2011) 41

Figure 2-10: Levels of themes that can be identified through thematic analysis 54

Figure 3-1: SwitchEV trial cohort flow chart and responsibilities (black text = SwitchEV consortium, including Newcastle University (NU) and red text = thesis author) 60

Figure 3-2: Seasonal carbon content of electricity in the UK by time of day 73

Figure 4-1: Number of recharging infrastructure hosts by user type (n = 140) 90

Figure 4-2: SwitchEV users (n=201) by age compared to UK national statistics (DVLA, 2012) 92

Figure 4-3: SwitchEV users (n = 189) by employment status (ONS QS602EW, 2011) 93

Figure 4-4: SwitchEV users (n = 178) by income bracket 93

Figure 4-5: User responses to the statement 'to do something for the environment' when asked why they took part in SwitchEV (n = 191) 94

Figure 4-6: Total frequency of EV recharging by time of day for all SwitchEV users in this study (n = 16,105 events) 95

Figure 4-7: Total frequency of EV recharging by time of day for all SwitchEV users in this study (n = 46,536h) 96

Figure 4-8: Total frequency of EV recharging for all SwitchEV users by user type (n=46,536h) 97

Figure 4-9: Total frequency of EV recharging by location (n=46,536h) 98

Figure 4-10: Carbon content of electricity during EV recharging using typical winter and summer recharging profiles based on all recharging events by all vehicles 99

Figure 4-11: Themes and sub-themes identified through thematic analysis 100

Figure 4-12: Users' responses to the post-trial statement 'I need to use work/public recharging posts in order to complete my daily trips' (n = 31) 105

Figure 4-13: Users' responses to the post-trial statement 'I recharge my EV at every opportunity' (n = 29) 106

Figure 5-1: Scree plot for clustering of driver recharging profiles 112

Figure 5-2: Overall recharging demand profiles for a four cluster solution 112

Figure 5-3: Overall recharging demand profiles for a five cluster solution 113

FIGURE 5-4: OVERALL RECHARGING DEMAND PROFILES FOR A SIX CLUSTER SOLUTION 113

FIGURE 5-5: ALLOCATION TO RECHARGING PROFILES BY CLUSTERING SOLUTION (N = 140) 114

FIGURE 5-6: CLUSTER ALLOCATION BY USER TYPE FOR NUMBER OF USERS (ABOVE) AND PERCENTAGE OF USERS (BELOW). 116

FIGURE 5-7: PROPORTION OF RECHARGING BY LOCATION IN EACH CLUSTER (EACH CLUSTER TOTALS 100%) 118

FIGURE 5-8: LARGE MORNING PROFILE RECHARGING EVENTS BY LOCATION (EACH USER TYPE TOTALS 100%) 120

FIGURE 5-9: LARGE MORNING RECHARGING PROFILES AT PUBLIC LOCATIONS BY USER TYPE (EACH USER TYPE TOTALS 100%) 120

FIGURE 5-10: LARGE MORNING WORK RECHARGING PROFILES BY USER TYPE (EACH USER TYPE TOTALS 100%) 121

FIGURE 5-11: SMALL MORNING RECHARGING DEMAND BY LOCATION FOR EACH USER TYPE (EACH USER TYPE TOTALS 100%) 122

FIGURE 5-12: SMALL MORNING PUBLIC RECHARGING PROFILES BY USER TYPE (EACH USER TYPE TOTALS 100%) 123

FIGURE 5-13: SMALL MORNING WORK RECHARGING PROFILES BY USER TYPE (EACH USER TYPE TOTALS 100%) 124

FIGURE 5-14: SMALL MORNING HOME RECHARGING PROFILES BY USER TYPE (EACH USER TYPE TOTALS 100%) 125

FIGURE 5-15: SMALL MORNING RECHARGING PROFILES AT OTHER LOCATIONS BY USER TYPE (EACH USER TYPE TOTALS 100%) 126

FIGURE 5-16: END OF WORKING DAY RECHARGING USE BY LOCATION 127

FIGURE 5-17: END OF WORKING DAY RECHARGING PROFILES BY LOCATION (EACH USER TYPE TOTALS 100%) 128

FIGURE 5-18: FREQUENCY OF RECHARGING EVENTS PER LOCATION BY USER TYPE FOR EARLY EVENING RECHARGING PROFILE USERS (EACH USER TYPE TOTALS 100%) 129

FIGURE 5-19: EARLY EVENING USER HOME RECHARGING PROFILES BY USER TYPE (EACH USER TYPE TOTALS 100%) 130

FIGURE 5-20: EARLY EVENING USER PUBLIC RECHARGING PROFILES BY USER TYPE (EACH USER TYPE TOTALS 100%) 131

FIGURE 5-21: EARLY EVENING USER OTHER LOCATIONS RECHARGING PROFILES BY USER TYPE (EACH USER TYPE TOTALS 100%)......132

FIGURE 5-22: LATE EVENING USER RECHARGING DEMAND BY USER TYPE AT EACH LOCATION (EACH USER TYPE TOTALS 100%) 133

FIGURE 5-23: END OF WORKING DAY USER HOME RECHARGING PROFILES BY USER TYPE (EACH USER TYPE TOTALS 100%) 134

FIGURE 5-24: LATE EVENING RECHARGING PROFILES AT OTHER LOCATIONS BY USER TYPE (EACH USER TYPE TOTALS 100%) 135

FIGURE 5-25: LATE EVENING RECHARGING PROFILES AT PUBLIC LOCATIONS BY USER TYPE (EACH USER TYPE TOTALS 100%) 136

FIGURE 5-26: HOME RECHARGING PROFILES BY CLUSTER (EACH CLUSTER TOTALS 100%)......137

FIGURE 5-27: OTHER RECHARGING PROFILES BY CLUSTER (EACH CLUSTER TOTALS 100%) 138

FIGURE 5-28: PUBLIC RECHARGING PROFILES BY CLUSTER (EACH CLUSTER TOTALS 100%)......139

FIGURE 5-29: WORK RECHARGING PROFILES BY CLUSTER (EACH CLUSTER TOTALS 100%)......141

FIGURE 6-1: NUMBER OF INTERVENTION PARTICIPANTS BY USER TYPE AND RECHARGING PROFILE (N= 21) 145

FIGURE 6-2: POTENTIAL CONTROL GROUP USERS BY USER TYPE AND CLUSTER 147

FIGURE 6-3: NUMBER OF PRIVATE USERS IN THE CONTROL (N=9) AND INTERVENTION (N=9) GROUPS BY RECHARGING PROFILE 149

FIGURE 6-4: PERCENTAGE POINT CHANGE IN THE RELATIVE PROPORTION OF OFF-PEAK RECHARGING (N = 21) AT ALL LOCATIONS......151

Figure 6-5: Percentage point change in the relative proportion of off-peak recharging (n = 21) by location 152
Figure 6-6: Percentage point change in total hours of off-peak recharging for users of home (n = 10) 153

Figure 6-7: Percentage point change in total hours of off-peak recharging for users of work recharging infrastructure (n = 11) 154

Figure 6-8: Percentage point changes in recharging infrastructure usage post intervention for all users in the control group at all locations (n = 21) 155

Figure 6-9: Percentage point change in recharging infrastructure usage post intervention period at home, for home users only (n = 10) 157

Figure 6-10: Percentage point change in recharging infrastructure usage post intervention period at work, for work users only (n = 11) 157

Figure 6-11: Percentage point change in total hours of off-peak recharging before and after the intervention period (n = 21) 159

Figure 6-12: Percentage point change in the carbon content of electricity during EV recharging post intervention using the winter CO_2 profile (n = 21) 161

Figure 6-13: Percentage point change in the carbon content of electricity during EV recharging post intervention using the winter CO_2 profile (n = 21) 162

Figure 6-14: Percentage point change in off-peak recharging frequency post intervention by location (n = 21) 165

Figure 6-15: Percentage point change in recharging infrastructure usage post intervention for users of home recharging infrastructure (n = 10) 166

Figure 6-16: Percentage point change in recharging infrastructure usage post intervention for users of work recharging infrastructure (n = 14) 167

Figure 6-17: Percentage point change in frequency of infrastructure usage before and after the intervention (n = 21) 169

FIGURE 6-18: PERCENTAGE CHANGE IN RECHARGING INFRASTRUCTURE USAGE POST INTERVENTION PERIOD FOR USERS OF WORK RECHARGING INFRASTRUCTURE (N = 15) 171

FIGURE 6-19: PERCENTAGE POINT CHANGE IN OFF-PEAK RECHARGING POST INTERVENTION FOR ALL USERS BY POST-INTERVENTION MONTH (N = 21) 173

FIGURE 6-20: PERCENTAGE POINT CHANGE IN CARBON CONTENT OF ELECTRICITY DURING EV RECHARGING POST-INTERVENTION USING THE WINTER CARBON CONTENT PROFILE (N = 21) 175

FIGURE 6-21: PERCENTAGE POINT CHANGE IN THE CARBON CONTENT OF ELECTRICITY DURING EV RECHARGING POST-INTERVENTION USING THE WINTER CARBON CONTENT PROFILE (N = 21) 176

FIGURE 6-22: COMPARISON BETWEEN TOTAL HOURS OF RECHARGING AND PERCENTAGE POINT CHANGE IN OFF-PEAK RECHARGING BEHAVIOUR (N=21) 180

FIGURE 6-23: USERS RESPONSES TO THE POST-TRIAL STATEMENT SMART METERS WOULD MAKE IT EASIER FOR ME TO RECHARGE DURING THE OFF-PEAK HOURS' (N = 46) 183

FIGURE 6-24: POST-INTERVENTION ATTITUDE TO RECHARGING INFRASTRUCTURE ACCESS SCENARIOS (MEMBERSHIP SCHEME N = 15 AND PAYG N = 14). 184

FIGURE 7-1: HOME RECHARGING PROFILES FOR SWITCHEV, CABLED AND MINI E USERS 192

FIGURE 7-2: WORK RECHARGING PROFILES FOR SWITCHEV AND CABLED USERS 193

List of Tables

Table 2-1: Targets for the installation of EV recharging units by 2020 for a sample of EU member states and the EU overall (European Commission, 2013). 16

Table 2-2: Number of recharging posts installed in the NE PiP network by year (Charge Your Car, 2013) 20

Table 2-3: Carbon content of electricity generation and transmission in the UK by power source(Department of Energy and Climate Change, 2013b) 31

Table 2-4: UK public climate change concern (n= 2051) (Department of Energy and Climate Change, 2013a) 49

Table 3-1: SwitchEV trial vehicle performance specification 62

Table 3-2: Switch EV user cohort start and end months. 65

Table 3-3: Number of focus groups and participants 69

Table 3-4: Carbon content of electricity generation in the UK by power source (Department of Energy and Climate Change, 2013b)....72

Table 4-1: Total number of Nissan and Peugeot users by cohort (n = 140).89

Table 4-2: Total frequency of EV recharging by time of day for all SwitchEV users in this study (n = 16,105 events) 96

Table 4-3: Percentage of durations between the end of a trip and the start of a recharging event by location (each location total = 100%)....101

Table 5-1: Number (percentage) of users allocated to each recharging profile for four, five and six cluster solutions 114

Table 5-2: Large morning recharging profile correlation coefficients between recharging profiles at public recharging infrastructure ..121

Table 5-3: Large morning recharging profile correlation coefficients between recharging profiles at work recharging infrastructure....122

Table 5-4: Small morning recharging profile correlation coefficients between recharging profiles at public recharging infrastructure ..124

Table 5-5: Small morning recharging profile correlation coefficients between recharging profiles at work recharging infrastructure 124

Table 5-6: Small morning recharging profile correlation coefficients between recharging profiles at home recharging infrastructure 125

Table 5-7: Small morning recharging profile correlation coefficients between recharging profiles at other recharging infrastructure ...126

Table 5-8: Early evening recharging profile correlation coefficients between user group profiles for home recharging 130

Table 5-9: Early evening recharging profile correlation coefficients between recharging profiles at public recharging infrastructure ..131

Table 5-10: Early evening recharging profile correlation coefficients between recharging profiles at other recharging locations 132

Table 5-11: Late evening recharging profile correlation coefficients between recharging profiles at home recharging locations 134

Table 5-12: Late evening recharging profile correlation coefficients between recharging profiles at public recharging locations 135

Table 5-13: Late evening recharging profile correlation coefficients between recharging profiles at home recharging locations 136

Table 5-14: Correlation coefficients between users following different recharging profiles for recharging at home 138

Table 5-15: Correlation coefficients between users following different recharging profiles for recharging at other locations 139

Table 5-16 Correlation coefficients between recharging profiles at public locations 140

Table 5-17: Correlation coefficients between recharging profiles at work 141

Table 5-18: Summary statistics for the five recharging profiles.............143

Table 6-1: Key characteristics of intervention participants and the number of exact matches in the potential control group user pool 147

TABLE 6-2: NUMBER OF PRIVATE USERS IN THE CONTROL GROUP (N= 9) AND INTERVENTION GROUP (N = 9) BY PEAK RECHARGING PERIOD 149

TABLE 6-3: QUARTILE VALUES OF THE PERCENTAGE POINT CHANGE IN THE RELATIVE PROPORTION OF OFF-PEAK RECHARGING (N = 21) BY LOCATION 152

TABLE 6-4: WILCOXON SIGNED RANK TEST RESULTS FOR MEDIAN PERCENTAGE POINT CHANGE IN THE RELATIVE PROPORTION OF HOURS OF OFF-PEAK BY LOCATION (N = 21) 152

TABLE 6-5: CONTROL GROUP QUARTILE VALUES OF THE PERCENTAGE POINT CHANGE IN THE RELATIVE USAGE OF RECHARGING INFRASTRUCTURE POST INTERVENTION (N = 21) 156

TABLE 6-6: WILCOXON SIGNED RANK TEST RESULT FOR THE CHANGE IN THE PROPORTION OF RECHARGING HOURS POST INTERVENTION (N = 21 PER LOCATION) 156

TABLE 6-7: CONTROL GROUP PERCENTAGE POINT CHANGE IN THE CARBON CONTENT OF ELECTRICITY PER RECHARGING EVENT POST INTERVENTION USING THE WINTER CO_2 PROFILE..160

TABLE 6-8: PERCENTAGE POINT CHANGE IN THE CARBON CONTENT OF ELECTRICITY PER RECHARGING EVENT POST INTERVENTION USING THE SUMMER CO_2 PROFILE 162

TABLE 6-9: QUARTILE VALUES OF THE OVERALL PERCENTAGE POINT CHANGE IN OFF-PEAK RECHARGING POST INTERVENTION BY LOCATION (N = 21).......................165

TABLE 6-10: QUARTILE VALUES FOR PERCENTAGE POINT CHANGE IN FREQUENCY OF INFRASTRUCTURE USAGE POST INTERVENTION (N = 21) 169

TABLE 6-11: QUARTILE VALUES FOR PERCENTAGE POINT CHANGE IN RECHARGING INFRASTRUCTURE USAGE POST INTERVENTION AT HOME (N = 11)....................170

TABLE 6-12: QUARTILE VALUES FOR PERCENTAGE POINT CHANGE IN RECHARGING INFRASTRUCTURE USAGE POST INTERVENTION AT WORK (N = 15) 171

TABLE 6-13: QUARTILE VALUES FOR PERCENTAGE POINT CHANGE IN OFF-PEAK RECHARGING POST INTERVENTION FOR ALL USERS BY POST-INTERVENTION MONTH (N = 21) 174

TABLE 6-14: QUARTILE VALUES FOR PERCENTAGE POINT CHANGE IN CARBON CONTENT POST-INTERVENTION USING THE WINTER CARBON CONTENT PROFILE (N = 21) ..175

TABLE 6-15: QUARTILE VALUES FOR PERCENTAGE POINT CHANGE IN CARBON CONTENT OF EV RECHARGING POST INTERVENTION USING THE SUMMER CARBON CONTENT PROFILE (N = 21) 176

TABLE 6-16: QUARTILE VALUES FOR PERCENTAGE POINT CHANGE IN FREQUENCY OF RECHARGING BY THE PERIOD OF DAY FOR HOME RECHARGING POST INTERVENTION (N = 11) 177

TABLE 6-17: PERCENTAGE OF TOTAL RECHARGING TAKING PLACE BY TIME OF DAY POST INTERVENTION FOR USERS OF HOME RECHARGING INFRASTRUCTURE (N = 11) 178

TABLE 6-18: TOTAL HOURLY RECHARGING FREQUENCY BEFORE AND AFTER THE INTERVENTION 180

Abbreviations

CABLED	Coventry and Birmingham Low Emission Vehicle Demonstrator
DECC	Department of Energy and Climate Change
EV	Electric vehicle
FTS	Future Transport Systems
GHG	Greenhouse gas
GT	Grounded Theory
IPA	Interpretative Phenomenological Analysis
ITS	Intelligent Transport Systems
NE PiP	North East of England Plugged-in Places
NU	Newcastle University
Org Ind	Organisation Individual user
OLEV	Office for Low Emission Vehicles
Org Pool	Organisation Pool user
P2W	Pump to Wheel
PAYG	Pay as you go
PiP	Plugged-in-Places
TA	Thematic analysis
TSB	Technology Strategy Board
ULCVD	Ultra Low Carbon Vehicle Demonstrator
UNFCCC	United Nations Framework Convention on Climate Change
V2G	Vehicle to Grid
W2P	Well to Pump
W2W	Well to Wheel

1. Introduction

1.1. Research Background

Targets for carbon emission reductions have been set both in the UK and overseas in order to mitigate the effects of climate change. For example, the UK Climate Change Act 2008 set the target of reducing carbon emissions by 80% compared to 1990 levels by 2050 (Department of Energy and Climate Change, 2008). Furthermore, the EU has introduced targets to reduce carbon emissions of 20% by 2020 and 80-95% by 2050, compared to 1990 levels (European Commission, 2011).

These carbon emissions targets have created a policy environment that aims to encourage the uptake of the electric vehicle (EV). The benefit of the EV over conventional internal combustion engine (ICE) powered vehicles becomes apparent when the life cycle of the fuels used to power vehicles is considered. The well to pump phase of a fuel life cycle refers to the emissions generated by the extraction, processing and transportation of the fuel to the point where it is stored in the vehicle fuel tank. Pump to wheel refers to the emissions generated by the burning of the fuel at the point of use. Although EVs do not generate emissions at the point of use, there are equivalent well to wheel estimates defined across the life cycle of electricity through the power generation and distribution process.

The precise quantities of these carbon emissions are dependent on the sources of power generation in a given country. For example, in 2009 the UK average carbon content of electricity was 544gCO_2/kWh and the typical EV energy use of 0.2kWh/km (Kemp *et al.*, 2010). Therefore, the Well to Wheel emissions associated with an EV were 109cCO_2/km. The Well to Pump (W2P) emissions for diesel are equivalent to 61gCO_2/km (DEFRA, 2010). The lowest pump to wheel (P2W) carbon emissions from a non-EV on sale in the UK 2013 was the diesel powered Renault Clio, with carbon emissions of 83gCO_2/km. This results in well to wheel (W2W) emissions of 144gCO_2/km (Society of Motor Manufacturers and Traders, 2014). Therefore, by encouraging drivers to purchase EVs, emissions from the transportation sector, contributing to carbon targets, can be reduced.

Due to the carbon emission savings offered by EVs, financial incentives to purchase EVs are offered in 17 EU member states, including the UK. These include government rebates and reduced road tax throughout the vehicles lifetime. The total number of EVs registered globally more than doubled between 2011 and 2012, from 45,000 to 120,000. By 2020 it is anticipated that global EV sales will be between 3.3 and 7.7 million per annum (International Energy Agency, 2013; Pike Research, 2013). Increasing the number of EVs in the market creates a requirement for recharging infrastructure to be developed in order to allow EVs to connect to power distribution networks as required by users. Plans to develop mass recharging infrastructure networks at home, public and workplace locations have been put in place. In total, there is a target for 8 million recharging posts to be installed across the EU by 2020, with 1.2 million in the UK (European Commission, 2013).

When implementing policy in any field, it is important to consider and manage any unintended consequences on other sectors. This is because there have been previous policies in one area that have impacted on other areas (Jones, 2012). For example, in the UK, the decision to allow individuals to choose schools and hospitals, irrespective of distance of travel or mode required, has generated additional demands on the transport sector (MRC Maclean Hazel, 2009). The consequence of developing recharging infrastructure networks is the increase in demand for electricity from the existing power distribution networks requiring more capacity at peak periods in order to supply the electricity to recharge EVs (Huang and Infield, 2010; Kemp *et al.*, 2010; Jones, 2012; Tie and Tan, 2013).

There are concerns that current UK power distribution network will be overloaded if EVs are recharged during on-peak hours, as this is when existing power demand from other sectors is high. An EV market penetration of 10% could create the need for £36 billion of investment in grid strengthening if all EVs were recharged during the on-peak hours (Pudjianto *et al.*, 2013). Devices called smart meters have been proposed in order to manage demand from EV recharging. They allow recharging to be delayed using a timer. Smart meters can be used in conjunction with reduced energy prices of up to 50% as an incentive for users to utilise this functionality. The smart meter is integrated into government policy as it is envisaged that EV driver recharging demand can be managed such that peak recharging does not coincide with the existing periods of high demand for electricity. This is reliant on the assumption that the price of electricity will be a sufficient tool to manage recharging behaviour. The existing demand for power is generally at a minimum from midnight onwards (Kemp *et al.*, 2010; National Grid, 2012); therefore the role smart meters is manage the recharging of EVs such that peak demand occurs during the 'off-peak' period between midnight and 07:00h (Andersen *et al.*, 2009; Kiviluoma and Meibom, 2011; Office for Low Emission Vehicles, 2011; Hedegaard *et al.*, 2012).

The assumption that recharging demands can be managed using a combination of financial incentives and smart meters have underpinned studies defining theoretical recharging profiles. Research by Kang and Recker (2009), Mullan *et al.* (2011) and Wang *et al.* (2011) defined theoretical recharging profiles. There was a consensus that the policymakers assumption that implementation of a smart meter strategy with financial incentives can facilitate off-peak recharging is correct.

This assumption has also been tested in real world trials. For example, the MINI E trial in Oxford concluded that vehicles would be recharged off-peak, at home. Similarly, the Coventry and Birmingham Low Emission Vehicle Demonstrator (CABLED) trial concluded that EV recharging would take place at home, overnight. Whilst these trials have demonstrated that home based recharging can be managed using smart meters and financial incentives, both MINI E and CABLED took place in regions where there was limited non-domestic recharging infrastructure. MINI E users did not have access to a non-domestic recharging network. CABLED users had access to 36 recharging posts at 12 sites, of which six where in Birmingham and six were in Coventry. Also, poor reliability of these existing posts was reported by drivers (BMW Group, 2011; Bruce *et al.*, 2012).

Therefore, whilst the findings of these studies can be used to predict drivers home based recharging infrastructure usage, they can’t be considered applicable to the recharging behaviour of users in regions with a high density recharging infrastructure. This is because they do not indicate how much recharging would take place away from the home. Neither do they indicate when and where this recharging might take place. Furthermore, they do not evidence whether the presence of smart meters and financial incentives at home would influence the utilisation of non-domestic recharging infrastructure. This is important because the underlying assumptions regarding the role of smart meters and financial incentives in government policy have yet to be verified in realistic real-world conditions.

This thesis aims to address this research gap. The study area for this research is the North East of England. This region is suitable due to the funding received as part of the UK Government Plugged-in-Places (PiP) scheme. This was a scheme which provided regional funding in order to develop the EV recharging infrastructure that is considered necessary to create EV friendly environments and increase the number of EVs on the road. Between April 2010 and June 2013, there were 1163 recharging posts installed in the region, of which 401 were in homes, 312 were at workplaces and 413 were at public locations. This high density of recharging infrastructure makes this region suitable to act as a case study.

Data for this research were collected from SwitchEV. This was a real world deployment trial of commercially available EVs that took place in the North East of England between 2011 and 2013. Recharging data were available by logging data from the CANBus of these vehicles. This is an on-board system through which communications between on-board microcontrollers and devices are transmitted. GPS devices were installed in all EVs taking part in the trial. This allowed the location, time of day and duration of all recharging events to be quantified. In total there were 23 Private users, 43 Organisation Individual users and 74 Organisation Pool vehicles (with multiple users), leasing the EVs for typically six month trial periods.

In order to further understand the recharging behaviour recorded from in-vehicle loggers, focus groups and questionnaires were conducted as part of SwitchEV. Full access to all transcripts and questionnaire responses was available for this research. There was scope, for questions pertinent to this research, to be added to the larger SwitchEV questionnaire and focus group discussions. Additionally, there was provision to offer financial incentives to a sub-set of drivers to recharge off-peak and for some further questions, specific to this financial intervention, to be included in the questionnaires and focus groups.

1.2. **Research Questions**

The research questions, within the context of a region with a high density, non-domestic recharging infrastructure were;

- What are the typical recharging demand profiles of EV users and subsequent differences in the carbon content of electricity used to recharge EVs?
- Can financial incentives be used as a tool to manage EV recharging demand? If not, what else should be explored?
- Are there any actual or perceived barriers preventing EV drivers recharging during the off-peak hours?

1.3. **Aim and Objectives**

The aim of this research was to define and understand the recharging profiles of EV drivers in a region with a dense recharging infrastructure, to quantify the environmental impact of this recharging behaviour and to assess the effectiveness of financial incentives as a recharging demand management tool.

The objectives of this research were:

- Process raw data available from SwitchEV trials to define recharging profiles of EV users;
- Identify a suitable data clustering technique and apply it to the measured recharging demand profiles to identify common recharging traits within the dataset;

- Apply a qualitative analytical methodology to identify patterns within the focus group and interview discussions;
- To design an intervention process to test the effectiveness of recharging demand management;
- Recruit drivers for this intervention and quantify the effectiveness of financial incentives as a demand management tool; And
- Identify and apply a suitable statistical methodology to quantify whether or not there was a statistically significant change at a known level of confidence in off-peak recharging post-interventions.

1.4. Scope of Research

This study aims to define the recharging demand profiles of users taking part in the SwitchEV trials. These profiles were defined based on the number of hours of recharging that had taken place in each hour of the day. These events were based on data made available for this research by the SwitchEV project consortium that were collected from in-vehicle loggers at a frequency of 1Hz and aggregated into individual recharging event data. Recharging locations were based on the five categories defined by the Technology Strategy Board (Fast, Home, Other, Public and Work).

The intervention offered users a financial reimbursement that was proportional in value the amount of electricity that they had used to recharge during the off-peak hours. This was based on a typical unit value of electricity. This research did not offer variable rates to test the sensitivity to different reimbursement values.

1.5. Thesis Structure

Chapter two of this thesis is the literature review. This provides an outline of the policy background to this research, the relationship between the EV and power generation sector, some previous research into EV recharging demand profiles, recharging data from other real-world trials and a review of statistical methods that could be used to cluster the recharging data and identify patterns within the focus group discussion.

Chapter three describes the methodological approach undertaken within this research project. This begins by presenting the approach taken by the SwitchEV consortium in order to recruit drivers, install recharging infrastructure and generate the data that are available for analysis in this research. The processing and analysis of these data and the design, user recruitment and analysis of the interventions are then described.

Chapter four describes the data collected for this study, the driver demographics and the analysis of the focus groups and interviews.

Chapter five presents the identification of typical recharging profiles within the dataset and an in-depth analysis of these profiles. The carbon content of electricity during EV recharging is quantified for each of the recharging profiles. This section concludes by making recommendations as to how recharging demand could be managed.

The intervention results are presented in chapter six. This begins with a review of the characteristics of users agreeing to take part in the intervention study. The process of selecting a representative control group is then presented followed by the impact of the interventions, which was quantified by analysing behavioural changes in both the control and intervention group of users.

Chapter seven presents a discussion of the results, the conclusions of this research, a comparison of these results with previous studies and recommendations as to future policies that should be implemented. It then identifies future research that is required.

Chapter eight is a list of references used in this thesis and chapter nine lists all dissemination and awards associated with this research.

2. Literature Review

2.1. Introduction

This literature review begins by describing how policy has evolved in such a way as to encourage the uptake of the battery electric vehicle (EV). Government incentives for the purchase of EVs and a review of the early market of EV adopters are presented. These topics are reviewed in order to provide context to the need for this research. The EV market is growing, has political backing and further research is needed into recharging behaviour.

One of the key barriers to EV uptake is the need to install both a domestic and non-domestic network of recharging infrastructure which is needed to facilitate growth in the EV market. The policy and development of EV recharging infrastructure within the UK is then outlined. Finally, an in-depth review of related activities in the North East of England region is presented.

The link between the power generation sector and the electric vehicle is then explored. The need for EV recharging to be managed and the role of smart meters and financial incentives are detailed. The environmental benefit of off-peak recharging is then investigated in a review of available methods for calculating the carbon content of electricity. The current power demand and generation in the UK is then presented.

Theoretical recharging profiles of EV drivers from previous studies are identified, analysed and discussed. This is followed by a description and critique of some real world EV deployment studies in the UK, including some of the results from SwitchEV. The peaks and distributions of recharging demand profiles are reviewed. This is in order to understand the behaviour of EV drivers in other regions, and allow the recharging profiles quantified in this study to be compared with those recorded elsewhere. This is important as other trials are testing vehicles in regions with differing recharging infrastructure provision and means of access. In order to inform the design of the intervention process for this study, literature regarding intervention design is presented. This includes a review of the use of financial incentives, goal setting and feedback, and the presentation of information to users.

There are two sections which review the methodological approaches that could be adopted for this research and identify the most suitable options. The first methods section is dedicated to cluster analysis, which was applied to the recharging profiles of EV drivers. The second methods section reviews the approach taken to qualitatively analyse the data from the focus groups and driver interviews.

2.2. **Policy Evolution**

The policy push toward the adoption of electro-mobility is a result of a gradual change in attitudes toward climate change and the environment over the previous decades. This review section explores the evolution of key policy documents and the interplay between UK and EU policy.

The UK Government policy on the environment has previously taken a market based approach, evident in the 1990 environmental white paper entitled ‘This Common Inheritance’. This paper stated that *“the oldest and best way of controlling the pace at which we use up natural resources is to let the market work. If one resource is in short supply, its price goes up, and somebody develops alternatives”*. The belief was that government should not use policy to influence the market regarding the use of energy and resources, but instead to allow the market to take the lead (UK Government, 1990).

A shift in attitudes toward climate change and emissions at a global level began in 1992 when the United Nations Framework Convention on Climate Change (UNFCCC) was signed. One of the challenges highlighted in the UNFCCC was the need to reduce the GHG emissions from privately owned vehicles and to reduce road congestion in cities (United Nations, 1992). The Kyoto Protocol to the UNFCCC was signed in 1997. This set legally binding targets for each nation with regard to greenhouse gas (GHG) emission reductions. Targets varied by nation. For example, the target for the UK was to reduce emissions by 12.5% by 2012 and 20% by 2020, relative to 1990 levels. These targets refer to the overall carbon emissions generated by a given nation across all sectors. (United Nations, 1998; Haita, 2012). There were no transport-specific targets and was no known evidence of any policy promotion of electric vehicles at this time.

As global attitudes started to shift towards a low carbon future, a greater focus on environmental policies was required at the European level in order to effectively tackle climate change. Previous EU policy had focussed on economic development and trade. The concept of sustainable growth was not officially included into EU law until 1993 (Monar and Wessels, 2001). Furthermore, environmental issues were not integrated into new policies. This limited the focus on environmental legislation, whilst focusing on economic and social issues. The Treaty of Amsterdam, signed in 1997, ensured that environmental policy was to be integrated into other EU policy areas, including transportation, in future years (Official Journal of the European Communities, 1997).

One such field to benefit from the integration of sustainable development into EU policy is transport and the concept of electrified transport; electro-mobility. The concept of electro-mobility for private cars did not initially receive much attention from high-level policymakers. The EU 2001 Transport White Paper introduced the concept of electro-mobility as part of a long term strategy for sustainable transport in Europe. At this stage it was considered that hybrid electric vehicles showed *‘great promise’*, whilst the battery electric vehicle would serve niche markets such as municipal vehicles and public service vehicles (European Commission, 2001).

A larger role for the EV was envisaged by the Department for Transport in 2004. The document ‘*A network for 2030’* highlighted the future challenges and vision for transport in the UK. Whilst the focus was primarily on modal shift and congestion reduction, the need for a transition to low emission vehicles was identified, with battery electric and hydrogen considered the most realistic and feasible options in the short to medium term. (Department for Transport, 2004).

A key publication in 2006 was the '*Stern Review on the economics of climate change'*. This study highlighted the need for global action to be taken to reduce carbon emissions from human activity. The levels of GHGs in the atmosphere have increased rapidly in the past three hundred years, from 280ppm (parts per million CO_2) before the Industrial Revolution to 430ppm as of 2006. If there were no changes to the rate of flow of annual emissions, the GHG levels in the atmosphere would reach 550ppm by 2050; almost double the pre-Industrial Revolution levels. Globally, the rate at which GHGs were emitted was increasing at the time of this study. The 550ppm level will be reached by 2035 if current trends continue, fifteen years ahead of Sterns original prediction. A consequence of reaching the 550ppm threshold is that there would be a 77% probability of a rise of at least two degrees in global temperatures. There is an economic benefit to reducing emissions. The costs of following a path to carbon stabilization at 550ppm by implementing measures to reduce carbon and GHG emissions give cost savings of $2.5 trillion, in net present value terms. Given current emissions levels, at the time the report recommended a UK targets of 60% minimum reduction by 2050, relative to 1990 levels (Stern, 2006).

In 2007, the EU developed a roadmap to 2020. Targets were set to reduce GHG emissions by 20% relative to 1990 levels by 2020. (European Commission, 2007). Furthermore, in 2007 the UK government commissioned '*The King Review of Low Carbon Cars'*. This was a study investigating the scope for the UK to meet the 60% minimum target, outlined by Stern (2006), from private cars and small vans. This study concluded that there is a need for transport to be electrified, with the battery electric vehicle playing a key role in an electro-mobile future (King, 2008).

The UK Climate Change Act 2008 set the UK the legally binding target of reducing GHG emissions by 80% by 2050, relative to a baseline of 1990 GHG emission levels (Department of Energy and Climate Change, 2008). This further created a policy environment favourable towards the EV within the UK.

Additionally in 2008, the EU launched the European Green Car Initiative (GCI) as part of the EU Economic Recovery Plan and the EU 2020 Strategy in helping the EU to achieve a sustainable future. It identified climate change, energy security and pollution as key challenges to the European automotive sector, and sets in place a plan for the transition to a future, low carbon economy. The installation of recharging infrastructure and research into the usage and impact of EV recharging on power distribution networks has been identified (European Commission Directorate-General for Research, 2010). As well as creating a suitable policy environment, the GCI aims to facilitate the electrification of road transport through research and development. Over 50 collaborative research projects have been funded. Areas awarded funding include battery design, manufacture and disposal, wireless recharging technology, power train systems and recharging station deployment and management (European Commission Directorate-General for Research, 2010).

In 2011, further EU targets of 80-95% relative to 1990 levels for GHG emissions reductions for 2050 were set (European Commission, 2011). This furthered the case for the role of the EV as part of a low carbon future.

Globally, the EV accounted for 0.02% of the total passenger car fleet at the end of 2012 (International Energy Agency, 2013). The barriers to EV uptake are the high purchase price, limited range, lack of public recharging infrastructure and a lack of public knowledge regarding low emission vehicles (Kemp *et al.*, 2010; Ozaki and Sevastyanova, 2011; Tsang *et al.*, 2012; Carley *et al.*, 2013).

2.3. **EV Early Adopters, Purchase Incentives and Future Market Trends**

In order to overcome the cost barrier to EV purchase, incentives have been put in place in order to facilitate the growth of the EV market. In the UK, from 2010, individuals purchasing an EV have been able to reclaim 25% of the purchase price (up to £5000) under the governments Plug-in Car Grant (Office for Low Emission Vehicles, 2010). In addition, 16 other EU member states have also offered financial incentives to encourage the purchase of EVs. Typically these were either in the form of tax incentives for the purchase of an EV or paying either no or reduced emissions/ environmental taxes (European Automobile Manufacturers Association, 2013). Similarly, the US government authorised federal tax credits for the purchase of electric vehicles in 2009 (Inland Revenue

Service, 2009). This facilitated growth in the EV market, with global EV sales rising from 45,000 in 2011 to 113,000 in 2012 (International Energy Agency, 2013).

Given that the EV accounted for less than 1% of the global vehicle fleet at the end of 2012 (International Energy Agency, 2013), the current users of the EV can be considered to be ‘innovators’ and ‘early adopters’. This is based on the ‘diffusion of innovation’. This concept describes how technologies are adopted by the mass market at each phase of the product life cycle. This theory was originally developed by Rogers (1964). It was proposed that the first 2.5% of people to invest in a new technology or process can be considered ‘innovators’. The next 13.5% are ‘early adopters’, followed by ‘early majority’ (next 34%), ‘late majority’ (next 34%) and ‘laggards’ (final 2.5%).

This theory has since been used in studies of the uptake of broadband internet (Park and Yoon, 2005), credit cards in China (Worthington *et al.*, 2011), online teaching and instruction in higher education (Hixon *et al.*, 2012), SMS based e-government services (Susanto and Goodwin, 2013) and smartphones (Lee, 2014).

The characteristics of the innovators/ early adopters of electric vehicles have been defined. Deloitte (2010) have defined the early adopters of EVs as young to middle aged individuals, with above average income and typically belong to households with two or more vehicles. Campbell *et al.* (2012) considered EV early adopters to be young to middle aged homeowners with a high socio-economic status from a detached or semi-detached household with more than one vehicle. Carley *et al.* (2013) conducted a survey of major US cities to identify the characteristics of individuals who expressed intent to purchase an EV. It was found that highly educated individuals with environmental concerns were the most likely to express intent to purchase an EV. Purchase cost was found to be the main inhibitor of EV uptake.

Furthermore, a choice modelling simulation of future EV uptake has suggested that marketing of EVs should focus on the combined economic and environmental savings they offer, rather than focusing purely on the emissions benefits over conventional vehicles (Tran *et al.*, 2013). The reason that these characteristics are linked to early adopters of EV could be due to individuals who display these characteristics possessing knowledge regarding the financial and environmental benefits of adopting a low emission vehicle. This knowledge was found to be the only significant difference between individuals purchasing hybrid electric vehicles and the general consumer market (Ozaki and Sevastyanova, 2011). This indicates that the early adopters of electric vehicles are not driving the EV purely due to environmental concerns, and that cost is a significant motivating factor.

Estimates have been made regarding the size of both the UK and global EV fleet size in future. Arup (2008) forecast that there will be between 0.5 million to 5.8 million EVs in the UK by 2030. Updated estimates have been made by National Grid (2013). In 2020, it is predicted that there will be between 32,000 and 140,000 full battery electric vehicles and between 128,000 and 420,000 hybrid electric vehicles on UK roads. By 2030 it is predicted that there will be between 72,000 and 576,000 new battery electric vehicle registrations and between 828,000 and 2.6 million hybrid electric vehicle registrations in the UK.

It has been estimated that there will be 1 million new electric vehicles registered in the EU27 member states in 2020, of which approximately 300,000 will be pure electric and 700,000 will be plug-in hybrid electric. By 2030, there will be 4.6 million new electric vehicle registrations per annum, of which approximately 1.7 million will be battery electric vehicles and 2.5 million will be plug-in hybrid vehicles (Proff and Kilian, 2012).

There is evidence of growing momentum in the global EV market. There were 180,000 EVs registered at the end of 2012. This was more than double the 45,000 sales in 2011. It is estimated that there could be over 20 million EVs globally by 2020, with sales figures reaching 7.2 million per annum (International Energy Agency, 2013). A lower estimate of 3.3 million sales per annum has been made by Pike Research (2013).

Although a number of different estimates have been made, all indicate that there will be growth in the number of EVs on the road, both in the UK and globally. This growing number of EVs will create a demand for recharging infrastructure (both at home and at non-domestic recharging locations), and generate increased demand for electricity.

2.4. EV Recharging Infrastructure

This section provides a review of the development of EV recharging infrastructure and future policy targets. This review begins by discussing recharging infrastructure at the European level and is followed by plans for the development of recharging infrastructure and demand management within the UK. The recharging infrastructure development within the North East of England is then described in detail. Finally, this section is concluded with an overview of development and targets for recharging infrastructure installation within China and the United States in an attempt to place UK plans in context worldwide.

2.4.1. European Union

As part of the development of recharging infrastructure in Europe, the Green eMotion project was announced in April 2011. This is a €42million project, funded under the European Green Car Initiative. This is a four year project which aims to develop and test the large scale public recharging infrastructure that is seen as necessary to encourage drivers to move away from ICE powered vehicles. Several locations have been selected as demonstrator sites. In Spain, over 1000 posts will be installed in Barcelona, Madrid and Malaga. In Germany, 3600 posts are to be sited in Berlin. In Italy, there will be 400 posts in Pisa and Rome. In Ireland 3,500 recharging posts will be installed nationwide. Denmark will have 2000 posts installed in Copenhagen, Bornholm and Malmo (Green eMotion, 2011).

Proposed targets for EU nations recharging infrastructure deployment by 2020 have been set for 2020 (European Commission, 2013). These targets cover the number of domestic and number of public recharging posts. The seven largest targets, along with the EU total, can be seen in Table 2-1.

Member state	**Target number of recharging posts**	**Number of publicly accessible recharging posts needed (10% of total)**
France	969,000	97,000
Germany	1,503,000	150,000
Italy	1,255,000	125,000
Netherlands	321,000	32,000
Portugal	460,000	46,000
Spain	824,000	82,000
UK	1,221,000	121,000
EU Total	**8,000,000**	**800,000**

Table 2-1: *Targets for the installation of EV recharging units by 2020 for a sample of EU member states and the EU overall (European Commission, 2013).*

It can be seen that the total target number of recharging posts, which includes public and non-public (both domestic and work), is 8 million by 2020 for the EU. Of the total number of recharging units for each nation, it has been agreed that 10% should be accessible to the public (European Commission, 2013).

The investment in multiple European cities under the green eMotion project, along with the EU targets for further development, indicates that there is likely to be a significant increase in EV recharging infrastructure across the EU by 2020. These plans indicate that there is agreement among EU governments that there is a significant role for EVs to play in a more sustainable future for transport. In the context of this thesis, the analysis to be undertaken is within a region with an already high density recharging infrastructure. Therefore, results from this research can help inform policy in other cities that are developing infrastructure now, before the anticipated growth in the EV market is realised.

2.4.2. UK Government Plans for EV Recharging Infrastructure

The Document ‘Making the connection: The plug-in vehicle infrastructure strategy’ (Office for Low Emission Vehicles, 2011) outlines the plans for recharging infrastructure development for EVs in the UK. It states that there will be three main components to the national recharging infrastructure network.

These are:

- Recharging at home
- Recharging at work
- Recharging in public places

The UK government expects EVs to be predominantly recharged at home overnight, when demand for power is at its lowest and the evening peak demand has passed. Additionally, organisation vehicles can be parked at a depot and recharged overnight. Work based recharging will be used primarily for top up recharges but also to act as the main source of recharging for vehicles that do not have access to home recharging or that are travelling long distance. The development of a national recharging infrastructure is considered to be an important element in making the EV competitive with ICE powered equivalents. This is because a public recharging infrastructure can increase the range of the EV beyond what could be achieved by recharging at home (Office for Low Emission Vehicles, 2011).

2.4.3. UK Plugged-in-Places Programme

In support of the development of a national public recharging infrastructure, the UK government committed £30 million of funding to the ‘Plugged-in-Places ‘(PiP) programme, which commenced in 2010. This programme provided match funding to businesses, consortia and local authorities to support the installation of EV recharging infrastructure in an initial eight regions across the UK, as seen in Figure 2-1.

Figure 2-1: UK Plugged-in-Places regions (Office for Low Emission Vehicles, 2011)

The target was for 8500 recharging posts to be installed nationally in homes, at places of work and at public locations by May 2013 (both PiP-funded and private investment). PiP started in 2010, initially in the North East of England, London and Milton Keynes (Office for Low Emission Vehicles, 2011).

By March 2013, there were approximately 4000 recharging posts installed through the PiP program, of which 65% were publicly accessible. It was also estimated that a further 5000 recharging posts had been installed by private organisations (Office for Low Emission Vehicles, 2013).

2.4.4. Plugged-in-Places in the North East of England

The PiP project in North East England (NE PiP) began in April 2010. Funding was available for all homeowners with access to off-street parking to have standard recharging posts installed, with 100% of the installation cost covered by a NE PiP grant. Funding of between 50-100% for posts at public or workplace locations was also offered for standard recharging posts, on condition that the host of this recharging infrastructure provided parking and electricity for NE PiP members. The delivery model for NE PiP was a membership scheme, whereby EV drivers pay an annual fee of £100 per year or a monthly fee of £10. This allowed users unlimited access to all public recharging posts and some of the workplace posts via the use of a smartcard. Additional pay as you go facilities were available to allow users from outside the North East of England region to use recharging posts through their mobile phones (Charge Your Car, 2012).

In June 2013, there were 1163 recharging posts in the NE PiP network. In total, 401 3/7kWh recharging posts were installed at domestic locations (referred to as ‘standard’ recharging posts in this study); 413 in public locations and 312 at workplaces. 12 50kV ‘fast’ recharging posts were in public locations. The cumulative number of posts in this network, installed by year, can be seen in Figure 2-2 and the location of the NE PiP region within the UK can be seen in Figure 2-3.

The number of recharging posts installed per year is illustrated in Table 2-2. The graph stops at the end of the application period for funding to install posts (Charge Your Car, 2013).

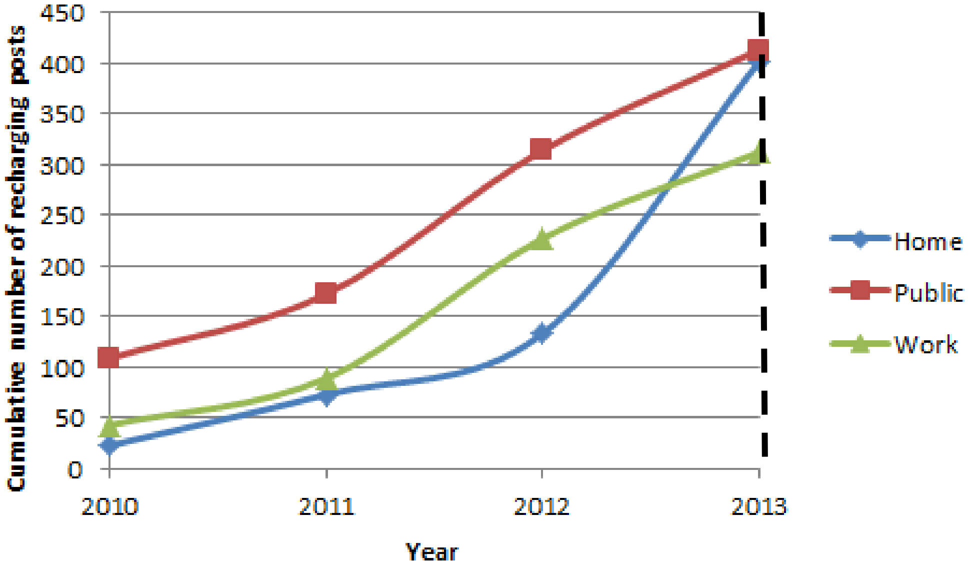

Figure 2-2: Cumulative number of recharging units installed in the NE PiP network (Charge Your Car, 2013)

	Recharging location			
Year	**Work**	**Public**	**Domestic**	**Fast**
2010	43	109	23	0
2011	46	63	50	6
2012	138	142	60	4
2013	85	99	268	2
Total	312	413	401	12

Table 2-2: Number of recharging posts installed in the NE PiP network by year (Charge Your Car, 2013)

Figure 2-3: Location of NE PiP network within the UK (above) and (below) recharging post locations within the region (pink circles)

Overall, there were a total of 152 non-domestic standard recharging posts and 23 domestic recharging units installed in 2010. In 2011, there were six fast recharging posts installed, 109 standard non-domestic recharging posts and 50 domestic recharging posts installed. 280 standard non-domestic recharging posts, 60 domestic recharging posts and four fast non-domestic recharging posts were installed in 2012. In 2013 an additional 184 standard non-domestic recharging posts, two fast recharging posts and 268 domestic recharging posts were installed. It is thought that this increase in domestic recharging infrastructure was due to an increase in applications before the deadline for the 100% installation cost grants.

Overall it can be seen that the recharging infrastructure in North East England was concentrated within the Tyne and Wear region, and in particular Newcastle city centre.

2.4.5. EV Recharging Infrastructure Policy and Installation in the United States and China

The US government has offered subsidies to encourage the private sector to develop EV recharging infrastructure networks across the country. The largest federal investment to date in EV recharging infrastructure was via the U.S. Department of Energy. 'The EV Project', which commenced in 2009, offered match funding of $115 million to recharging post manufacturer ECOtality in order to develop a nationwide network of recharging infrastructure. Target states were Arizona, California, Oregon, Tennessee, Texas, and Washington state, as well as the District of Columbia (The EV Project, 2013). In total, including EV project installations and commercial investments, there were 6268 recharging stations (some with multiple recharging posts) in total.

The Chinese governments' 12th Five Year Plan (2011-2015) outlines growth targets for the electric vehicle industry. A target of 220,000 public EV recharging posts to be installed by the end of 2015 has been set (Fulton, 2011). By the end of this five year plan, it is estimated that $764 million will have been invested in EV recharging infrastructure by China Southern Power Grid (China Energy Forum, 2012).

This highlights the large scale investment in non-domestic EV recharging infrastructure taking place in other key economies outside of the UK and the EU. The policy being implemented in the US and China is comparable that of the UK and EU in terms of the focus on the development of non-domestic recharging infrastructure. This indicates a consensus amongst policymakers that the development of non-domestic recharging infrastructure is crucial to making the market for EVs competitive with internal combustion engine (ICE) powered equivalents. An implication of this policy consensus is that any subsequent problems or issues that arise once the EV market develops are likely to be repeated globally.

2.5. **Impact of EV Recharging Demand on Power Distribution Networks**

The plans to expand domestic and non-domestic recharging networks will increase the demand for power placed on existing power generation and distribution networks. Therefore it is therefore important to understand the relationship between the EV and the power grid (Kemp *et al.*, 2010). At present, the role of the power supplier is to ensure that the demand for power is met at any given time. The owner of the power distribution network is responsible for providing the physical infrastructure that transfers power from the point of generation to where it is consumed. In the UK, National Grid owns and takes responsibility for the power distribution network. There are two key issues that present challenges to power suppliers and owners of power distribution networks. A challenge facing the owners of power distribution networks is that there are concerns that existing power distribution networks could overload due to additional electricity demand from EVs (Huang and Infield, 2010; O'Connell *et al.*, 2012; Oliveira *et al.*, 2013). Secondly, the sources of power generation and the time of day of recharging demand have an impact on the carbon content of electricity used to recharge EVs (McCarthy and Yang, 2010; Camus and Farias, 2012; Ma *et al.*, 2012)

Therefore, this section investigates current knowledge of the likely impacts of EV recharging during periods of existing high demand and the technologies that are proposed to manage this demand.

2.5.1. Impact of Additional Loads on Power Distribution Networks

There are concerns that power grids could overload if EVs are recharged during peak periods (Kemp *et al.*, 2010; O'Connell *et al.*, 2012; Oliveira *et al.*, 2013). This was tested for the UK electricity power network using a Monte-Carlo simulation of EV recharging demand by time of day, under the assumption that EVs are recharged immediately after drivers arrive at home on an evening. It was found that, with 20% market penetration for the EV in the UK, the power distribution system would need to be strengthened. This furthers the case for recharging demand management tools (Huang and Infield, 2010). However, this study did not take into account other new loads from other sectors that are potentially likely to be placed on the power distribution network in future years. In particular, it is anticipated that domestic power demand could increase by 40% due to growth of electric heat pumps. When these are taken into account, a 10% market penetration of EVs recharging would require a £36 billion investment to increase grid capacity should the EV recharge during on-peak hours (Pudjianto *et al.*, 2013). It is acknowledged that there is a great deal of uncertainty in the future demand for electricity *per se*, given the uncertainty of future energy sources, the uptake of sources of new electricity generation, refurbishment of existing sources, and demand management technologies notwithstanding the rise in population in the UK.

The potential for power grids to overload if EVs are recharged during on-peak hours creates a need to understand the recharging demands of electric vehicle drivers. By understanding these demands, the potential for power grids to overload can be planned for and managed. Furthermore, once these recharging demands are understood, the next important step is to develop technologies and procedures to effectively manage this recharging demand in order to ensure that, during the on-peak hours, recharging is minimised to levels that do not cause failure of the power distribution networks.

Demand management strategies are required in order to reduce the amount of grid strengthening that will be required should EVs achieve a higher market penetration. The vehicle to grid (V2G) concept proposes that an EV can be recharged at times of day where existing demand for power is low, thus minimising the impact of EV recharging and reducing the need for further investment in power network capacity. IEEE sample power systems have been used to simulate the effect of EV recharging. These are generic computer based models that are representative of general power distribution networks in terms of network topology and the power capacity of links within the system. These models were loaded with simulated EV recharging demands, both demand driven and managed. It has been determined that these networks have sufficient capacity provided that the EV loads are managed and do not occur during peak hours (Clement-Nyns *et al.*, 2011; Oliveira *et al.*, 2013).

The technologies through which V2G can be implemented are smart meters and smart grids. These technologies can delay electricity use, including EV recharging. This could be a time specific delay of several hours, ensuring that an EV is recharged during off-peak periods. Alternatively, power can be drawn dynamically to recharge EVs when demand is low. This would be implemented by the device receiving up to date power demand and generation information, and also communicating with other EVs to establish a mutually agreed order for access to electricity for recharging if this is beneficial from either a power network or carbon perspective. The advantage of drawing power dynamically is that it is the most efficient way of reducing demand on the grid. However, there is a drawback in that it removes control from the driver and may need to be overridden if a recharge is required within the same day or within a specific timeframe known to the driver. Furthermore, some drivers may always state that they need to recharge urgently in order to ensure that their vehicle is recharging in the fastest time (Andersen *et al.*, 2009; Kiviluoma and Meibom, 2011; Zhang *et al.*, 2011; Hedegaard *et al.*, 2012).

This literature review demonstrates that there is a technologically viable solution to the issue of recharging demand management. However, whilst these technologies provide a means to manage recharging demand, their effectiveness as standalone tools may be undermined as rely on human nature to use them and do not provide any incentive to users to utilise this functionality.

Pricing incentives can be used to incentivise users to utilise smart meters to manage their own electricity demand, by offering lower prices during periods where existing energy usage is low. This can be implemented using either real-time data or fixed rate tariffs that vary by time of day based on typical power demand (Andersen *et al.*, 2009; Zhang *et al.*, 2011; McHenry, 2013; Tie and Tan, 2013; Usman and Shami, 2013). Although these pricing incentives can be successful when the change in behaviour is perceived to be easy, daily routines and individual preferences also can play a role in determining the time of day of energy use. For example, whilst it is beneficial from an energy management perspective for an EV to be recharged during the off-peak hours, this may not be convenient or preferable for an EV driver. For example, users might need to recharge during the day to complete their journey (Hargreaves *et al.*, 2010; Hahnel *et al.*, 2013; Verbong *et al.*, 2013).

It is important that user views and opinions are used to inform the design and operation of the energy management process (Verbong *et al.*, 2013). Drivers have been found to make regular journeys with a degree of consistency that enables them to make good estimates of their own travel behaviour. The implication of this is that drivers could provide useful input data into energy management systems to aid their operation. For example, by entering the start time and end point of anticipated upcoming journeys in advance of the trips, a smart system would be able to ensure that an EV is recharged sufficiently to complete the trip by the time the journey begins, without recharging at the instant the EV is plugged in. However, it is accepted that it will not always be possible to shift recharging demand due to the operational requirements of a user (Hahnel *et al.*, 2013).

This indicates that, whilst smart meter functionality to delay EV recharging provides a technical solution, this should be implemented in conjunction with a system in which drivers are incentivised to utilise this functionality as much as possible. In the context of this thesis, this review highlights the importance of understanding driver views regarding recharging management and financial incentives, as these could be used to help inform future policy to maximise off-peak recharging and thus justified the need to carry out an analysis of focus group discussions regarding EV recharging.

2.5.2. Carbon Content of Electricity Used to Recharge EVs

The second issue regarding EV recharging, is the link between the carbon intensity of the power generation sources used to supply energy and the equivalent carbon content of EV trips. Emissions from vehicles are defined in several ways depending on the point in the life cycle of the fuel at which the emissions are generated. Ma *et al.* (2012) provide definitions for the different life-cycle emission measures of conventional fuels for ICE vehicles;

- *Well to Tank* (W2T) emissions are the emissions associated with the generation/extraction of the fuel used to power a vehicle and the transportation of the fuel to the point where it is stored within the vehicle (the fuel tank).
- *Tank to Wheel* (T2W) emissions are those which are generated at the point of use.
- *Well to Wheel* (W2W) emissions refer to the entire life cycle of the fuel (i.e. the W2T emissions plus the T2W emissions).

Electric vehicles do not generate any GHG emissions at the point of use and therefore have no tank to wheel emissions. All emissions associated with the life cycle of the fuel used to power electric vehicles occur during the well to tank emissions phase i.e. the generation and transmission of electricity (and the losses associated with this). The carbon content of electricity being used to recharge the vehicle’s batteries is dependent on the relative contribution to the total power being generated at any given time by each power source. If the carbon content of the electricity is known, and the energy used on a particular journey is known, then these can be combined together to calculate the emissions per kilometre. (William, 2010; Doucette and McCulloch, 2011). These emissions can vary depending upon the time of day that an EV is recharged. This is because the proportion of energy sources with a higher carbon content, such as coal, are used to ensure that demand is met during peak periods. This is explored further in Section 2.6 (Elgowainy *et al.*, 2009; Hadley and Tsvetkova, 2009; McCarthy and Yang, 2010; Camus and Farias, 2012; Ma *et al.*, 2012).

2.6. Power Generation and Demand in the UK

In order to understand the link between EV recharging and the power distribution network in the UK, this section reviews the current total power supply and demand on typical winter and summer days in order to identify existing peak periods.

The most recent data released by National Grid regarding variations in power supply and demand over a 24 hour period was from 2010, and were published in ‘Charts and Tables-Chapter 3 – Generation’ in the appendix of the 2011 Seven Year Statement (National Grid, 2011a). The National Grid has since stopped publishing Seven Year Statements, and instead published the first Ten Year Statement in 2012. This document contains total installed power generation capacity information and provides both historic and future peak demands but does not provide current demand across a typical 24 hour period (National Grid, 2012).

The total power generation capacity in the UK in 2010 was 79,400MW. The capacities of the individual power sources can be seen in Figure 2-4 (National Grid, 2011b).

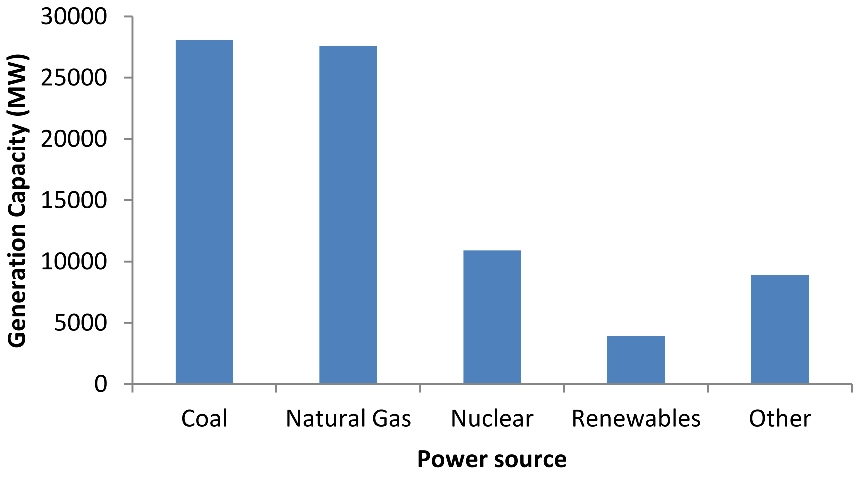

Figure 2-4: Electricity generation capacity in the UK by power sources (National Grid, 2011b)

Coal and natural gas accounted for 28GW and 27.5 GW of installed capacity respectively. This was approximately 70% of the total generation capacity.

Nuclear power accounted for 11GW of installed capacity, which was 14% of the total capacity, whilst renewable energy sources can generate up to 4GW of power, 5% of the total. The fluctuations in demand for power over a 24 hour period and the generation sources used to meet this demand, on both a typical winter and summer day, can be seen in Figure 2-5.

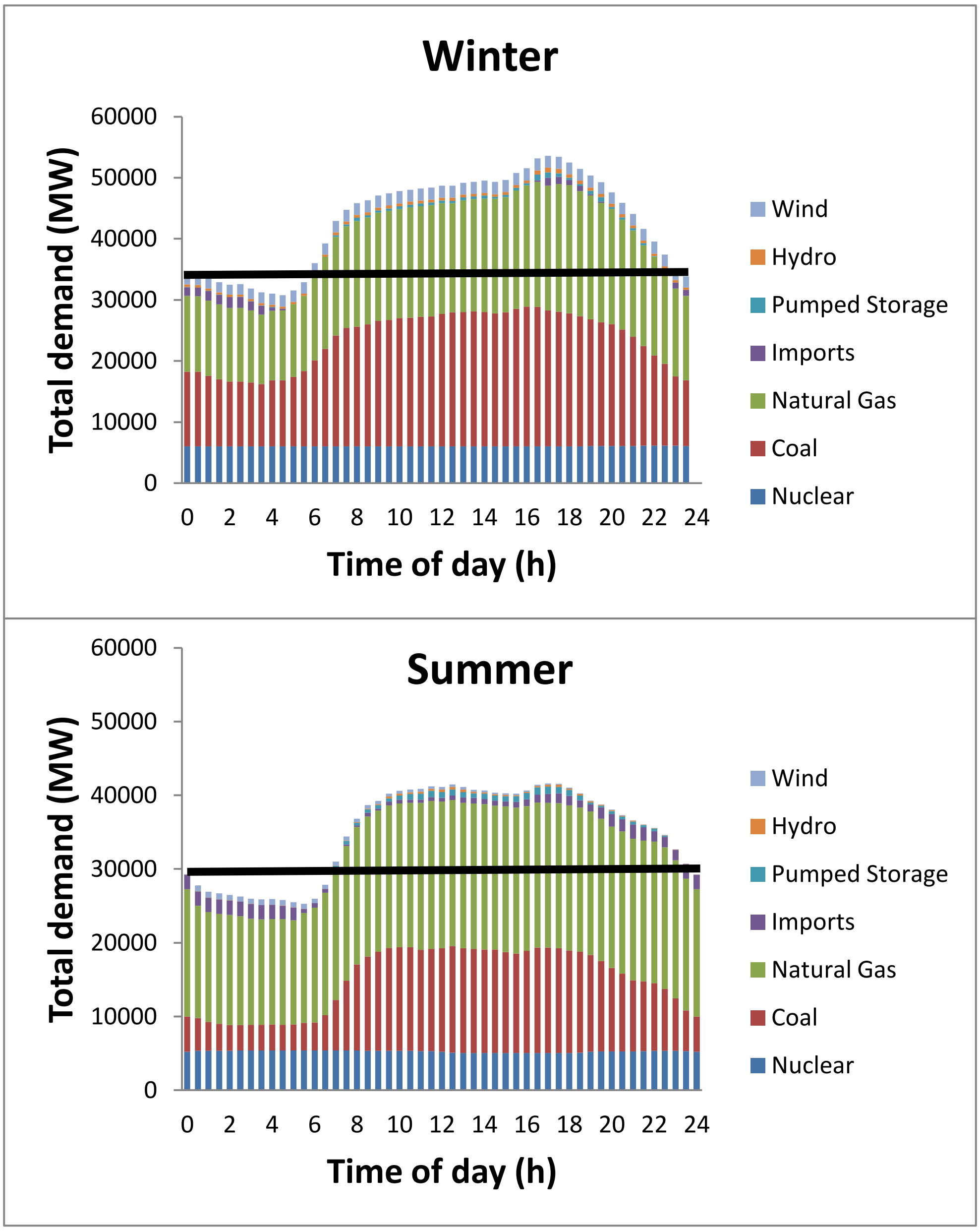

Figure 2-5: Power generation sources used in the UK on a typical winter day (top) and summer day (bottom) to meet electricity demand (National Grid, 2011a)

On the typical winter day in Figure 2-5, demand increased from a minimum of 30,797MW at 05:00h to 46,300MW at 09:00h, with a peak demand of 53,570MW at 17:30h. At the time of minimum demand: coal accounted for 35% of total power generation, gas accounted for 37.0% and nuclear accounted for 20%. During the demand peak, coal contributed 42% to the total power generated, gas 38% and nuclear 11%. On the typical summer day, the minimum demand peak of 25,267 MW occurred at 05:30h, amounting to 18% less than the peak demand in winter and occurring 30 minutes later. At this time, coal accounted for 15% of power generated, gas 59% and nuclear 21%. The maximum demand peak was 41,631MW, which was at 17:30h. This was 22% less than the winter evening peak and occurred at the same time. At this peak demand, coal contributed 34% to the total power generated, gas 47% and nuclear 12% (National Grid, 2011b).

In order to reduce demand during the peak hours, electricity providers can offer consumers variable electricity tariffs, whereby the price of a unit of electricity varies over a 24 hour period based on typical power demand. For example, the Economy 7 tariff in the UK offers participating customers reduced electricity costs of up to 50% during ‘off-peak’ hours. These are the seven hours of the day in which the overall demand for power is at its lowest. These hours are between 24:00h and 07:00h, and represent all power demand bars underneath the horizontal line in Figure 2-5 (British Gas, 2013; EDF Energy, 2013; Energy Choices, 2013). This industry standard definition of ‘off-peak’ hours is used throughout this thesis. The term ‘on-peak’ is used to refer to all other hours.

When considering EV-specific financial incentives to manage recharging, it is likely that the most economically effective measure for power grid operators to implement in order to encouraging off peak EV recharging is to adopt a time-of-use approach. This is where drivers are offered a reduced electricity tariff for recharging their EVs during specified off-peak hours of the day. Methods whereby electricity prices are adjusted in real-time are not likely to offer significant economic benefit to the grid operator to be a worthwhile investment (Lyon *et al.*, 2012).

2.7. **UK Carbon Content of Electricity Generation**

The carbon content of electricity is defined as the carbon produced when generating one kilowatt hour (kWh) of electricity. The carbon content of power generation is multiplied by a transmission loss factor to take losses during the transfer of power into account. For the disclosure period 01/04/2012 – 31/03/2013, the carbon content of electricity generation from each power source in the UK can be seen in Table 2-3. The transmission loss factor for this disclosure period was 1.11. This indicates that, due to energy losses within the system, 11% more energy than required at the point of use must be generated (Department of Energy and Climate Change, 2013b).

Source	**Carbon content (gCO_2/kWh)**
Nuclear	0
Coal	910
Gas	390
Other	590
Renewables	0

Table 2-3: Carbon content of electricity generation and transmission in the UK by power source(Department of Energy and Climate Change, 2013b)

2.7.1. Definitions of the Carbon Content of a Unit of Electricity

There are two ways in which the carbon content of a unit of electricity can be defined; the average carbon content or the marginal carbon content. In terms of EV recharging, the marginal carbon content is the carbon content of the additional electricity that is generated to meet demand due to EV recharging. (Hawkes, 2010). The average carbon content calculated by multiplying the carbon content of the average unit of electricity generated across all power stations in the UK multiplied by a transmission loss factor, based on the total generation at any given time (Kemp *et al.*, 2010; DEFRA, 2012).

The choice of average or marginal emissions factor is determined depending on the specific aim of the research. Ma *et al.* (2012), Camus and Farias (2012), McCarthy and Yang (2010), Elgowainy *et al.* (2009) and Hadley and Tsvetkova (2008) used the marginal carbon content to quantify the carbon emissions of the additional energy that would need to be generated due to the adoption of electric vehicles. On the other hand, studies by Pasaoglu *et al.* (2012), Howey *et al.* (2011), Kemp *et al.* (2010) and Barkenbus (2009) used the average emissions factor to estimate the carbon content of electricity being used to recharge EVs.

There are several problems associated with using the marginal emissions factor in EV research. One is that power generated at a specific site for a specific demand is mixed in with electrons carrying power from other sites as it is transmitted through national and regional networks. Secondly, even if it is assumed that extra power generated is attributed to the additional source of demand, it cannot be assumed that the most carbon intensive source, such as coal, will be generated for the purpose of EV recharging. In reality, energy traders representing energy suppliers will buy energy for their customers use based on a range of factors including whether they are on a green tariff and the relative cost at any given time. Practically, it is not possible for a researcher to obtain this information and, even if it were possible, the emissions would then be dependent on the users' energy supplier as well as their recharging behaviour. For these reasons, the average emissions factor is the most appropriate measure for this study.

2.7.2. Methods of Calculating the Carbon Emissions Factor

There are multiple methods available to calculate the carbon content of electricity. The fixed emissions factor approach multiplies energy use (kWh) by the carbon content associated with the consumption of the average kilowatt hour of electricity. This approach is recommended by the Department of Environment, Food and Rural Affairs (DEFRA) in the UK for use by companies when reporting emissions. DEFRA guidelines state that either the five year rolling average figure of 517gCO_2/kWh (from the period 2006 – 2010) should be used (DEFRA, 2012). This fixed emissions factor has been applied to quantify the carbon content of the energy used to recharge EVs (Barkenbus, 2009; Howey *et al.*, 2011; Pasaoglu *et al.*, 2012; Thomas, 2012).

However, the approach of using a fixed emissions factor reduces the reliability of the results. This is because, as power demand fluctuates (both seasonally and over any given 24 hour period), there are different relative proportions from each source of power generation contributing to the overall energy mix. Consequently, there are differences in carbon content both by time of day and time of year that need to be taken into account (Kemp *et al.*, 2010; McCarthy and Yang, 2010).

This has been achieved in previous studies by using a variable emissions factor taking fluctuations in carbon content into account. McCarthy and Yang (2010) applied an hourly average carbon content of electricity generation based on each month of the year. On the other hand, Jansen *et al.* (2010) adopted a different approach and applied a seasonal average for each hour of the day.

Kemp *et al.* (2010) recommended the use of real time data (available at five minute intervals in the UK) to quantify carbon content of electricity. As the time between the measurements of power generation outputs decreases, the accuracy of the subsequent carbon content estimation increases. A problem with using a measure of carbon content that varies on a day-to-day basis is that it does not allow the impact of incentives designed to modify recharging behaviour of different users across a trial period on the carbon content of electricity used to recharge to be isolated with statistical confidence from the day to day changes. This is due to the difference in carbon content being from a function of both the time of day and duration over which the EV was recharged. Therefore, a typical carbon content profile is required to be defined to understand the impact of recharging behaviour on the carbon content of electricity used to recharge an EV.

2.8. Theoretical EV Driver Behaviour and Recharging Demand Profiles

The demand for EV recharging over a 24-hour period is called a recharging profile. One of the difficulties in future casting recharging demand is the sparcity of data available of real world recharging behaviour to measure recharging demand, given such early days of the availability of EV technology worldwide. Therefore, researchers have attempted to predict recharging demand using methods other than recording real world data from EVs. These are reviewed in this section.

Morrow *et al.* (2008) predicted that recharging that would take place at home in the evening. This was based on a combination of daily travel data from both the 2001 US National Household Travel Survey and also recharging trends of privately owned hybrid electric vehicles recorded from Idaho National

Laboratory trials. The hybrid electric vehicles on trial had one peak in recharging demand per day, which occurred in the late evening between 20:00h and 22:00h. However, it is noted that this was based on data that were collected in regions with limited non-domestic recharging infrastructure access. Additionally, the travel data was used to predict recharging demand under different recharging infrastructure development scenarios. Night time recharging was predicted at residential garage and apartment complex locations. Business hours recharging was predicted at commercial locations.

Four recharging profiles were proposed by Kang and Recker (2009) using activity based modelling. This allows recharging times to be predicted based on knowledge regarding the location of a driver at any given point in the day. Recharging demand and vehicle location were predicated on information from travel diaries. It was assumed that EVs would be recharged immediately upon completion of their daily trips in the recharging profile called *'End of travel day'*. In the *'Uncontrolled home'* recharging profile (home recharging available but with no smart meters or financial incentives to manage demand), EVs were recharged at domestic locations after drivers return home on an evening. If a mass non-domestic infrastructure is installed, the '*Publicly available electricity'* recharging scenario assumed that EVs were always recharging (when the battery was not at 100% SOC) when parked at any public location. Under the assumption of smart meter functionality being utilised, the *'Controlled charging'* profile assumed EV recharging started after 22:00h.

Three recharging profiles were developed by Mullan *et al.* (2011). EVs were only recharged between 16:00h and 23:00h in the *'evening only'* recharging profile. This scenario assumed vehicles were recharging upon returning home on an evening. Recharging only took place between 22:00h and 07:30h in the *'night time'* recharging profile. EV recharging was spread between 19:30h and 02:00h using the smart meters functionality to delay recharging in the *'controlled'* recharging profile.

Wang *et al.* (2011) developed three scenarios for EV recharging. The first involved EVs being recharged at home without any constraints, with a peak in demand at 17:00h. The second profile used smart meter functionality to delay all recharging from the first scenario by three hours. Scenario three assumed delayed night-time recharging of EV's and scenario four assumed that the two controlled recharging profiles had larger peaks, which occurred between 19:00h and 24:00h.

Camus *et al.* (2011) and Druitt and Früh (2012) suggest the cost to the driver of recharging and the operational needs of the driver are factors which will determine real world recharging profiles.

A comparison of these theoretical recharging demand profiles can be seen in Figure 2-6.

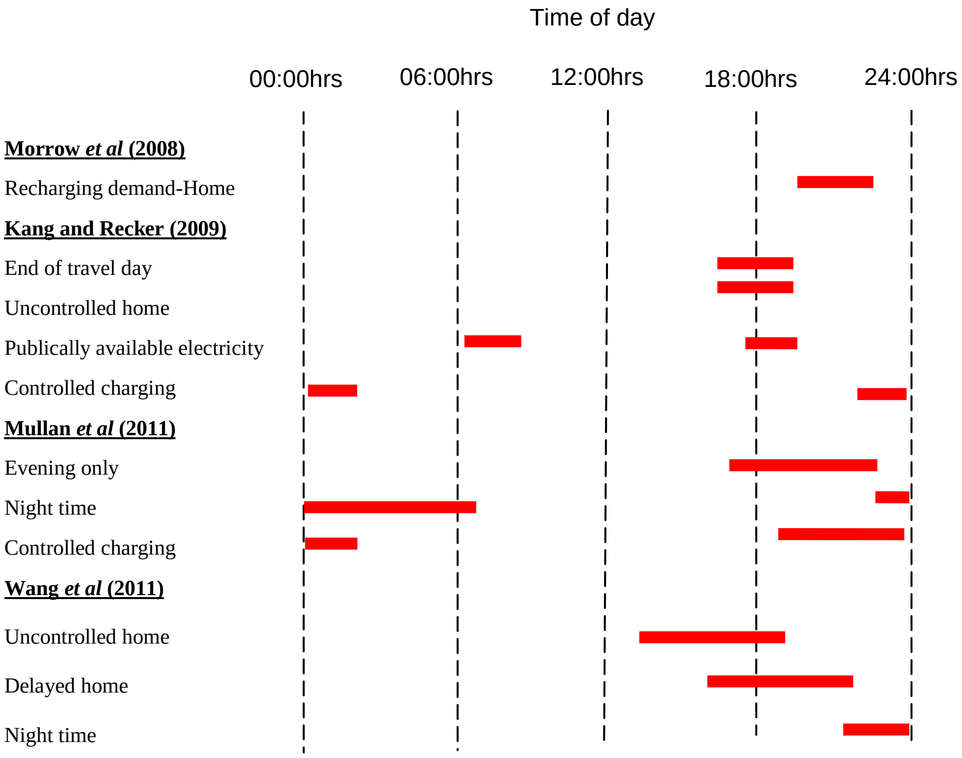

Figure 2-6: Comparison of theoretical recharging demand profiles defined in literature by different researchers

These theoretical studies have provided an outline of the recharging behaviours that would be expected. The researchers that have generated theoretical recharging demands have made generated similar outputs. There is an agreement that drivers will recharge upon arrival at a location, for example home, unless smart meters are used to delay demand. There was agreement amongst these researchers that smart meters will be an effective tool to manage recharging demand. Furthermore, the demand profiles generated in these studies match the UK government policy for smart meters to pay a key role in delaying recharging demand. The assumptions regarding recharging behaviour appear to be logical. However, a weakness of these studies is that the assumptions that they make regarding recharging behaviour and driver response to smart meters is that they are not verified in these studies with real world data.

2.9. Review of Real World Recharging Data

The previous section reviewed theoretical recharging demand profiles due to a lack of real world data. However, there are a number of real world trials of EVs in which recharging demand data have been recorded and published. These are reviewed in this section.

2.9.1. CENEX Smart Move Trials

The Centre of Excellence for Low Carbon and Fuel Cell Technologies (CENEX) Smart Move trials deployed four EVs for six months in 2010, in the North East of England. These trials aimed to investigate the potential for EVs to be integrated into organisations' vehicle fleets for pool use. All vehicles were fitted with data-loggers and a GPS device. 2% of the local authority recharging events and 10% of private sector vehicle recharging events took place at home. The remainder were conducted at work. (Carroll and Everett, 2010). This illustrates the workplace-centric recharging habits of pool vehicles. The significance of workplace centric recharging of pool vehicles is that the times at which vehicles are plugged in at work could differ from those recharging at home. If this is the case, it is important to identify the nature of a vehicles use when attempting to develop technologies to manage recharging demand.

2.9.2. UK Ultra Low Carbon Vehicle Demonstrator Trials

The Ultra-Low Carbon Vehicle Demonstrator, funded by the Technology Strategy Board (TSB) involved eight consortia across the UK, consisting of a combination of manufacturers, academics, energy companies and public bodies conducting trials of low carbon vehicles (LCVs) between 2010 and 2013 (Everett *et al.*, 2011).

The aims of the ULCVD programme were:

- To expose EVs to a wide range of different drivers, driving styles and driving cycles;
- To analyse real world EV use through collection of key parameters via vehicle-logging equipment. All drivers/organisations involved in these trials had to agree to have data-logging equipment placed in the car to allow vehicle use and performance to be tracked. At a minimum, the following parameters had to be measured for each EV event (either a trip or a recharging event); Vehicle ID, Start time, end time, battery state of charge at beginning and end of event and location (defined by the TSB as Home, Work, Public, Other);
- To determine EV users opinions, concerns and perceptions of all aspects of owning and operating an EV over a prolonged period; and
- To understand the challenges of interfacing EVs with recharging infrastructure.

There were three London based trials. The first was the Ford Focus Battery Electric Vehicle trial involved 15 battery electric Ford Focus vehicles being leased to members of the public for a one year lease period. This study took place in Hillingdon, London, during 2010. The aim of this trial was to test the suitability of battery electric technology for future incorporation into Fords range of vehicles (Green Car Guide, 2009; Everett *et al.*, 2011; Ford Media, 2012). There were 10 public recharging posts in Hillingdon offering free electricity. Use of some of the bays incurred parking charges at standard rates (Hillingdon Council, 2012). The London Smart ED trial involved 100 Smart Electric Drive vehicles being leased to members of the public and organisations. Smart meters were installed at drivers' homes, and drivers could access 20 public recharging posts for a £75 annual membership fee (GreenWise Business, 2009; Everett *et al.*, 2011).The third London-based trial was the Toyota Plug-In Hybrid project. This was a one year project which commenced inJune 2010 and involved 20 vehicles being leased to both private and public sector organisations (Everett *et al.*, 2011).

In Glasgow, the Allied Vehicles Project started in October 2009 and finished in December 2010. There were 40 electric vehicles on trial; 10 Peugeot eExpert people carriers and 30 Peugeot ePartners. These vehicles were used as Glasgow City Council fleet vehicles (EV Perspective, 2009; Allied Electric, 2010; Everett *et al.*, 2011).

The EEMS Accelerate project aimed to provide funding to develop and road test high-end electric vehicles, to challenge public perceptions of EVs and to motivate further research and development in the British EV industry (AEA, 2012).

Recharging start times for all users across the entire ULCVD trial for year one can be seen in Figure 2-7.

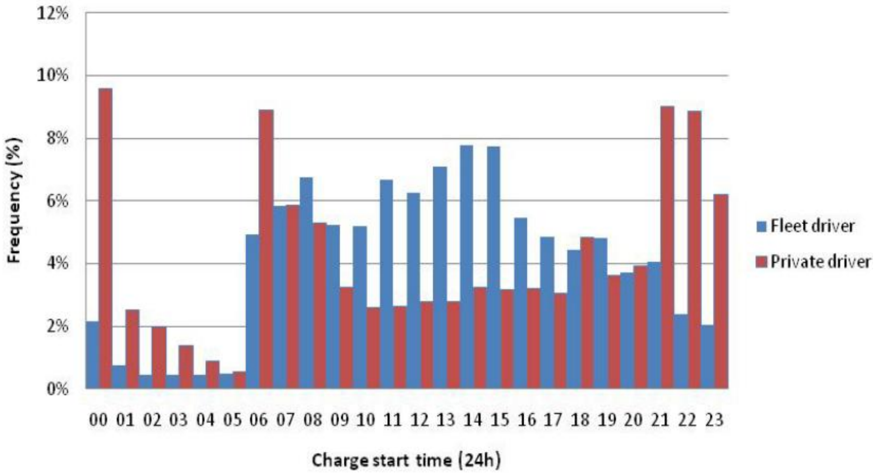

Figure 2-7: Frequency of the start time of recharging events by user types from the first year of the ULCVD trials (Everett et al., 2011)

The most frequent time for Private users to begin recharging was between 23:00h and 24:00h. 9.5% of recharging events started in this hour. 34% of recharging events started between 21:00h and 01:00h. For organisation users, the 73% of recharging events started between 07:00h and 19:00h. 46% of Private users recharging events started during this period of time (Everett *et al.*, 2011). Furthermore, when quantifying the relative usage of recharging infrastructure for the full ULCVD trial dataset, 97% of recharging took place at home for users with a home post installed. 83% of recharging took place at work for users with a work recharging post installed (Carroll *et al.*, 2013).

The significance of this is that the recharging data observed indicate that the type of use of a vehicle influences the recharging demand, with pool vehicles being recharged more during the working day and private vehicles on an evening or overnight. This is because pool vehicle recharging posts are at the place of work and private vehicle have dedicated recharging posts at home. Therefore, EVs for Private users are more likely to be recharged at the end of the day when the user arrives home from work, whereas the pool vehicles are recharged as the vehicle arrives at the workplace following a business-related trip or before workplaces are vacated in the evening. The implication of this is that when considering the recharging behaviour of a driver, it is important to link this to the location and time of day when they have access to their own dedicated recharging infrastructure.

2.9.3. Coventry and Birmingham Low Emission Vehicle Demonstrator (CABLED)

The Coventry and Birmingham Low Emission Demonstrators (CABLED) trials took place between 2010 and 2012. There were 110 EVs, which were leased to individuals and organisations for trial periods ranging between 12 weeks to six months. All users were required to have a recharging point installed at home (CABLED, 2012b). Participants had access to 36 public recharging posts, located at six sites in Birmingham and six sites in Coventry. All 36 recharging locations offered free electricity, and half of the sites (totalling 16 parking bays) offered free parking, with standard parking rates applied at the remaining 20 bays (CABLED, 2012a). The recharging demand and profiles by location for EV drivers in the CABLED project can be seen in Figure 2-8.

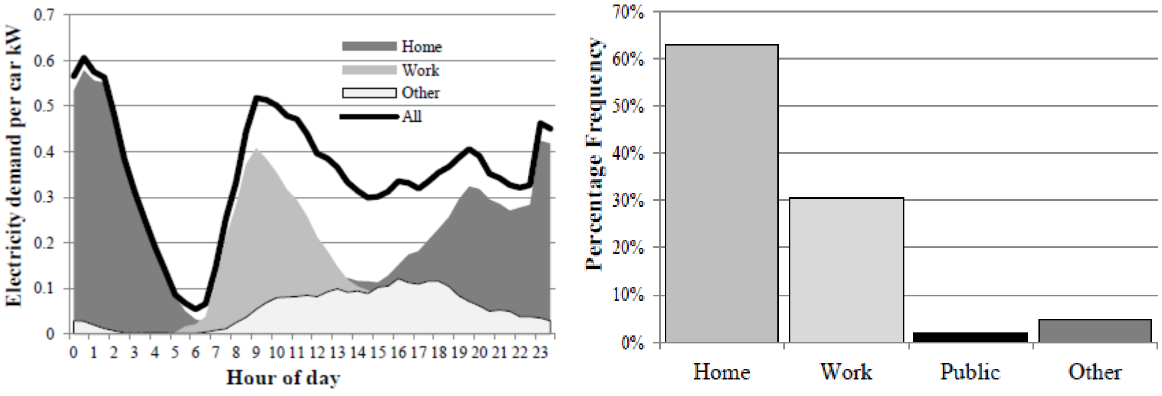

Figure 2-8: EV Recharging profiles by hour of day (left) and demand by location (right) in the CABLED project (Bruce et al., 2012)

As seen in Figure 2-8, 62% of recharging took place at home. This is likely to be because there were limited sites (12) across Birmingham and Coventry for non-domestic EV recharging. The public recharging infrastructure accounted for 2% of total recharging, and at the workplace accounted for 30%. Not all users had access to workplace recharging infrastructure. Of those users with both home and work, approximately 50% of the total number of recharging events took place at each location. There was a peak in recharging demand at home between midnight and 01:00hrs and at work between 09:00hrs and 10:00hrs (Bruce *et al.*, 2012). This suggests that the smart meters placed in users homes were effective in encouraging EV drivers to recharge off-peak. However, some drivers still recharged upon arrival at home and did not delay recharging.

2.9.4. BMW MINI E

The BMW MINI E field trials began 2009. Trials have taken place in Oxford, Paris, Berlin, Munich, Los Angeles, New York, Beijing, Shenzhen and Tokyo (BMW Group, 2011; Everett *et al.*, 2011).

The USA MINI E trial took place between June 2009 and June 2010. There were 450 vehicles leased at a monthly rate of US$850 (approximately £520 at 2010 prices). No specific provisions were made for non-domestic recharging infrastructure. All drivers had home recharging units installed, which could be reprogrammed to recharge overnight. Recharging demand information was obtained through participant travel diaries. It was found that some vehicles were recharged overnight, and others were recharged whenever the vehicles were parked at home. It was speculated that this was due to some users having less expensive off-peak electricity tariffs (Turrentine *et al.*, 2011).

The UK MINI E trial was part of the ULCVD program and was open to members of the public who live and work in and around Oxford. Successful candidates were required to pay a £330/month lease fee. All drivers involved in this trial had a recharging unit installed in their home, with limited access to non-domestic recharging infrastructure. Smart meters were installed in drivers' homes, and off-peak electricity tariffs were offered. This trial collected EV usage data through a combination of vehicle logging systems, driver interviews and questionnaires (Oxford Brookes University, 2009; BMW Group, 2011; Everett *et al.*, 2011).

82% of EV drivers reported that 90% or more of their recharging events were completed at home. The MINI E driver recharging profile at home can be seen in Figure 2-9.

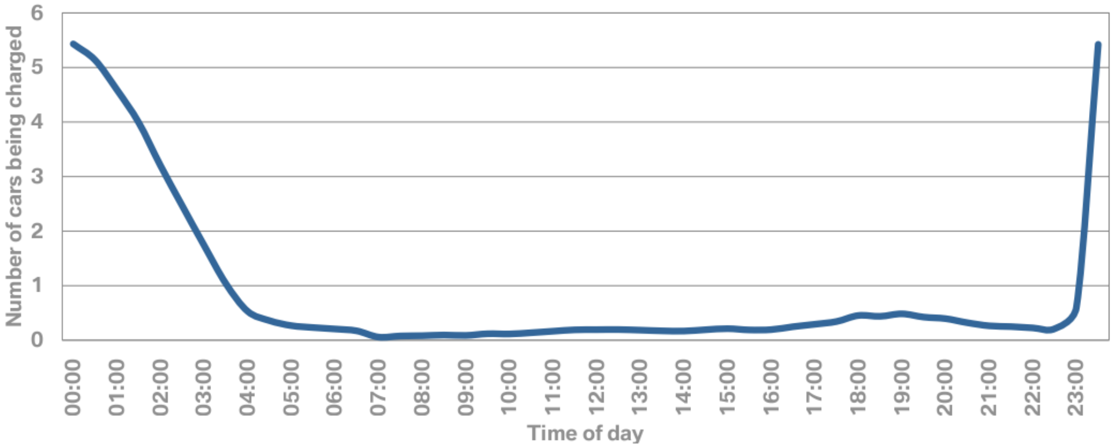

Figure 2-9: Recharging demand profile at home for UK MINI E trial participants (BMW Group, 2011)

It can be seen in Figure 2-9 that the majority of EV recharging was completed overnight. The smart meter at home, combined with a financial incentive, was effective in shifting the recharging of EVs into the off peak hours. Due to the lack of public recharging infrastructure available to the drivers, this study provides evidence of home EV recharging behaviour but does not give an indication of how the development of non-domestic infrastructure will impact these drivers recharging behaviour.

2.9.5. SwitchEV Trials

All data and results presented in this thesis were obtained through the SwitchEV trials. These trials took place in North East of England between May 2011 and May 2013. 44 EVs were leased to organisations for both individual and pool use, and to Private users. There were four successive six-month trial periods.

Recharging data were collected via in-vehicle loggers. See the methodology section for an in-depth review of driver recruitment, data-logger specifications, focus group design and recruitment, and relevant questions from the post-trial questionnaire.

The SwitchEV trial generated a unique dataset amongst the EV deployment studies. This is because a combination of private, Organisation Individual and Organisation Pool user types leased the vehicles across a region with one of the densest recharging networks in the world (NE PiP) via a membership scheme. Furthermore, all EVs in SwitchEV are commercially available, rather than experimental vehicles. Within the range of the EV, the distribution of trip lengths for the vehicles taking part in SwitchEV was similar to the distribution of trip lengths for all passenger cars in the UK (Blythe *et al.*, 2012). This suggests that the EV can be an effective replacement for an ICE vehicle and be utilised in a similar way.

The perceived need for the NE PiP public recharging infrastructure in the North East of England region has been tested. All energy transferred to the EV battery due to recharging events at public recharging stations were selected from the total dataset. A criterion was then set, which stated that if a vehicle could have completed all of its daily trips and still have 20% SOC remaining, then the use of the public recharging infrastructure was not a necessity. The energy used on the remaining trips for each day to enable the vehicle to reach home was then compared to the energy available in the battery from the previous home recharging event. It was found that 7% of the recharging events at the public recharging infrastructure were absolutely necessary. Furthermore, EVs were found to be parked in the bay at a recharging post for an average of three hours and 37 minutes after recharging their battery to full capacity (Higgins *et al.*, 2012). This suggested that the majority of public recharging was not needed, and that users are taking advantage of the use of the EV parking bays. This issue is explored further in the results section of this thesis.

2.9.6. EV Recharging Infrastructure Data

The role of smart meters and financial incentives has been explored using household data from two cities in the USA. The peak recharging time for EVs at home was at 01:00hrs in San Francisco. This is a city in which electricity providers incentivised off-peak energy use. However, in Nashville, where there are no such incentives, the peak demand for home EV recharging occurred at 20:00hrs (Schey *et al.*, 2012). This provides further evidence that smart meters and financial incentives can facilitate the management of EV recharging at home.

In terms of public recharging infrastructure, data have been collected from the ECOtality network in the USA. It was found that pricing mechanism can have an impact of the usage of public recharging infrastructure. Recharging posts with no out-of-pocket cost to the user recorded four times as many recharging events as those in which the user paid standard parking fees (Saxton, 2012). This provides real world evidence that EV recharging demand can be managed at non-domestic recharging locations through out-of-pocket pricing strategies.

2.10. Financial Incentives and Intervention Design

It has been identified that EV recharging during the on-peak hours could lead to power distribution network overload. Through a combination of theoretical recharging demand profiles and real world data, it has been determined that not all EV recharging will take place during the off-peak hours.

In order to influence behaviours, technologies need to be developed to deliver change through intervention or constraint. Therefore, smart meters have been proposed as demand management tools. The use of smart meters has been proposed to manage the recharging demand of EVs, influencing the recharging behaviour of EV drivers through intervention for the benefit of energy management. This has been proven to be effective when EVs are recharged predominantly at home and when there was no, or limited, access to non-domestic recharging infrastructure. This study aims to understand how recharging demand can be managed across a region with a well-developed non-domestic recharging infrastructure. Therefore, this section presents a review of behavioural interventions and how they can be applied to this study.

An intervention is an attempt to change or influence the behaviour of a person or group of people. The provision of information is the key element of an intervention. Previous studies into interventions focused on the management and usage of energy and electricity have combined an intervention with one or more of the following; financial incentives, goal setting and feedback (Hayes and Cone, 1977; Winnett *et al.*, 1978; Battalio *et al.*, 1979; Aigner and Lillard, 1984; Abrahamse *et al.*, 2007; Parag and Darby, 2009; Roy and Pal, 2009; Carrico and Riemer, 2011; Fischer *et al.*, 2011).

The success of an intervention can be affected by the way in which information is presented to the participants and the perceived difficulty of changing behaviour (Chatterton *et al.*, 2009; Van de Velde *et al.*, 2010; Whitmarsh *et al.*, 2011). These areas are explored in the following sections in order to inform the intervention design for this study.

2.10.1. Financial Incentives

Financial incentives are an important tool when attempting to change behaviour. Both policymakers and the general public believe that individuals will only change their behaviour to be more environmentally friendly through financial incentives and regulation (Pichert and Katsikopoulos, 2008).

Interviews with members of the public on the subject of attitudes toward the adoption of environmentally friendly behaviour have been conducted by Fischer *et al.* (2011). It was found that people believe that others are self-centred, and will only change their behaviour through a combination of strict regulation, drastic price changes and new technological innovations. Research by Shaw and Maynard (2008) in the field of recycling found that individuals were more willing to recycle if they were offered rebates on their council tax as a reward for changing their behaviour. This provides evidence that, in other related fields, financial incentives can be a success.

However, it has been suggested that the use of financial incentives alone is not the most effective approach to take. For example, if individuals are offered financial incentives to change behaviour, but do not receive focused information regarding the environmental benefits of behavioural change they may not be sufficiently motivated to make changes that are long lasting (Parag and Darby, 2009). Furthermore, households that have received guidance explaining how to increase their energy efficiency, reduced their energy use by 5.1%, compared to a control group whose energy use increased by 0.7% over the same period (Abrahamse *et al.*, 2007). As information regarding the environmental benefits of behaviour change becomes increasingly specific, there is a statistically significant increase in individuals' probability of making eco-friendly behavioural changes (Ek and Söderholm, 2010). This highlights the importance of accompanying financial incentives with information provision that explains why behavioural change is important and how behaviour can be changed, and why this approach was adopted in this thesis.

Information campaigns are particularly effective when the behavioural changes they are promoting are not costly or inconvenient (Gärling and Schuitema, 2007). This demonstrates the importance of understanding whether or not drivers perceive switching their recharging activity to off-peak hours as inconvenient. This is an issue that must be investigated and understood in this thesis. The reason for this is that by knowing drivers perceptions of the ease, or difficulty, of changing their behaviour in this region, and why they perceived this, future policy can be better informed.

2.10.2. Delivery of Information

The delivery of information can have an impact on the likelihood of an intervention achieving the desired result. For example, the information campaigns regarding energy efficiency in Sweden during the oil crisis in the 1970's have fostered long term, energy efficient behaviours and attitudes in many households across the country. The success of these campaigns has been attributed to the clear provision of information to the general public and that they highlighted the lower energy costs available to consumers (Lindén *et al.*, 2006).

A study of the UK general population's engagement with climate change has found that the following problems are perceived when information is presented; the overall information being confusing or conflicting, confusion regarding the links between environmental issues and their solutions, information overload and the information being inaccessible to non-experts (Lorenzoni *et al.*, 2007). Therefore, when conducting interventions, it is important that the information presented is precise, relevant and makes a clear link between the behavioural change being requested and the consequential benefit of this change.

Tailoring information to the target audience can make attempts to change behaviour more effective. For example, an intervention was conducted with the aim of changing working practices in vehicle maintenance garages to be more environmentally friendly. It was found that when information was tailored to individual workplaces, there was an increase in environmentally friendly practice. However, those that received non-tailored information did not see any significant change in working practice (Daamen *et al.*, 2001). This indicates that information should be tailored to the needs of the target recipients. Providing information in this way is advantageous because users receive only information that is specific to their situation, reducing the risk of information overload or individuals losing interest because they do not deem the intervention to be relevant to themselves (Abrahamse *et al.*, 2005). Therefore, users that do not have access to home recharging taking part in the interventions in this thesis were not advised to use the reprogrammable timers at home, ensuring that all information was tailored to the circumstances of each individual driver.

The response of an individual to environmental information is affected by the frame of the message. An individual will respond more positively when the positive environmental benefits due to a change in behaviour, are highlighted, rather than focusing on the negative environmental consequences associated with the user not changing their behaviour (Van de Velde *et al.*, 2010). Therefore, when providing information to users as part of this thesis, a positively framed message, stating the carbon savings that could be achieved via off-peak recharging, rather than a negative message emphasising the higher carbon content of electricity that would be used to recharge during the on-peak was formulated.

2.10.3. Impact of Users' Perceived Difficulty of Behavioural Change on Intervention Results

A key factor in determining whether individuals are likely to adopt more environmentally friendly behaviour is their perception of how easy this behaviour is to implement. If a particular action is deemed to be difficult or time consuming, individuals lose interest and motivation in the action. Changes in household behaviour are viewed as small and of minimal inconvenience. However, changes in the way people travel, for example making changes to a habitual journey or travel routine (e.g. a switch from driving to travelling by bus), have been proven to be perceived as '*difficult and substantial'*. Drivers will make changes to their current routine only if they perceive that there is a viable alternative to their current travel behaviour. However, relatively it is not perceived to be difficult to make changes to domestic energy conservation. A key challenge is to understand the barriers to behavioural change, as these need to be removed to make a behaviour change easy to implement and increase the likelihood of a change occurring and prevailing over time (Satoshi, 2006; Chatterton *et al.*, 2009; Whitmarsh, 2009; Whitmarsh *et al.*, 2011).

This highlights the importance of understanding the perceptions of drivers regarding the barriers to behavioural change. Therefore, in this study, feedback was sought from EV drivers upon completion of their trial to understand whether they perceived it to be difficult, or easy, to change their EV recharging behaviour. Also, upon completion of their trial period, drivers were asked to describe whether they encountered any barriers that were preventing them recharging off-peak.

2.10.4. Use of Feedback and Goal Setting

Providing feedback to participants can increase the effectiveness of an intervention (Staats *et al.*, 2004). Providing feedback is thought to be successful because it makes individuals aware of their current performance, especially if the feedback is instantaneous (Abrahamse *et al.*, 2007). In a study of workplace energy efficiency, in an office where staff were given information and feedback energy efficiency was reduced by an additional 7% compared to in a similar office that received information only (Carrico and Riemer, 2011). In the case of energy use, feedback is needed because consumers view energy use as ‘invisible’. Many individuals are not aware of their energy consumption and how this links with their lifestyles. Feedback is considered to bridge this gap by providing users with this knowledge and making energy use visible (Burgess and Nye, 2008). The key learning outcome from this literature is that providing feedback is important because it makes individuals more aware of their performance, thus making an intervention more effective.

Goal setting has been proven to be a successful approach. An intervention involving goal setting combined with user feedback, when looking to reduce household energy use, showed that households could increase energy savings by 21% (McCalley and Midden, 2002). Goal setting is not generally effective as a standalone approach, and is typically combined with an information campaign and financial incentives (Abrahamse *et al.*, 2005).

The author believes that it is important to draw a distinction between information and education. Information is generally simply a statement of fact resulting from the processing of data. However, what is believed to be more important is the implication of acting on that information, which the author refers to as knowledge, which delivers education giving lessons why it is important to act on the information.

2.10.5. Impact of Attitudes towards Climate Change and the Environment

It has been found that consumers expressing a greater concern toward climate change and the environment are more willing to adopt new technologies and initiate pro-environmental behavioural changes (Steg and Vlek, 2009; Kavousian *et al.*, 2013; von Borgstede *et al.*, 2013; Wicker and Becken, 2013). Therefore, it was important to understand what the attitudes of the sample of users in this study were toward climate change and to interpret these in the context of the attitudes of the general public.

Based on 2051 valid responses, the attitudes of the British public toward climate change, when questioned in March 2013, can be seen in Table 2-4 (Department of Energy and Climate Change, 2013a).

Level of concern	Frequency of response (%)
Very concerned	20
Fairly concerned	46
Not very concerned	23
Not at all concerned	10
Don't know	1

Table 2-4: UK public climate change concern (n= 2051) (Department of Energy and Climate Change, 2013a)

It can be seen that the majority of the British public were concerned about climate change. Therefore, the results of the intervention process undertaken in this thesis cannot be considered not to be representative of the general population due to a wider lack of environmental concern.

2.11. **Review of Statistical Methods for Data Clustering**

One of the objectives of this research is to define the typical recharging profiles of EV drivers in the SwitchEV trial. This requires a means of identifying characteristics of recharging demand profiles that are common to multiple users. One approach available is to cluster objects based on researcher-defined characteristics. However, this could be subject to researcher prejudice and not identify with the underlying trends governed by characteristic responses to questions which lay within the dataset. Therefore, this section reviews data classification algorithms that can be used to group data in an unbiased and statistically robust way.

The term ‘cluster analysis’ is a general term that describes any data classification algorithm that can be used to classify a number of objects into meaningful clusters according to known characteristics (Fraley and Raferty, 1998; Field, 2005). This statistical approach has been applied to a wide range of scientific fields, including the classification of; industrial faults (Yiakopouloulos *et al.*, 2010), coal types used for power generation (Pandit *et al.*, 2011), bone cyst fluid volumes (Docquier *et al.*, 2009) and faults in power systems (Mora-Florez *et al.*, 2009). Within transportation research, cluster analysis has been used for the classification of air quality and pollution on the road network (Chen *et al.*, 2008; Cairns *et al.*, 2011).

It can be seen that clustering algorithms have been adopted by researchers in transportation, as well as other analogous disciplines. This indicates that these methods are widely applicable and are considered to be robust.

2.11.1. Methodological Approaches to Data Clustering

There are two methodological approaches that can be taken when using cluster analysis; hierarchical and non-hierarchical. Hierarchical techniques are based on the theory that objects can be related based on their relative closeness. Individual data points are aggregated into progressively larger clusters, based on the shortest distance between the clusters. Non-hierarchical techniques partition individual datum points into groups that have no hierarchical relationships within the group. Initially, a pre-determined number of cluster centres are randomly generated. Each data point is then allocated to the nearest of these cluster centres. Each of the cluster centres is then recalculated. All data points are then reallocated into clusters based on their closeness to these new cluster centres. This iterative process continues until all data points remain within the same cluster between iterations. Non-hierarchical methods are prone to producing different solutions due to the random starting position of the cluster centres. An advantage of using the non-hierarchical approach is that it has a greater computational efficiency (Fraley and Raferty, 1998; Grimm and Yarnold, 2000; Anderson, 2003).

The hierarchical approach is more robust as it does not generate multiple solutions because it is not subject to random starting co-ordinates. However, it is more computationally inefficient. Where practical to do so, the hierarchical approach should be the preferred option. However, if computing limitations restrict the research, then the non-hierarchical approach should be used.

2.11.2. Defining the Distance between Objects

Once the methodology for partitioning the data has been decided, the next step is to define how the distances between the data points being clustered are calculated.

The Euclidian distance metric measures the point to point length of the vector between two elements in space. The Euclidian distance can be squared. The Squared Euclidian distance increases the weighting of objects that are farther apart. The Manhattan distance uses the absolute difference between the co-ordinates of two points rather than the direct shortest path (Euclidian). The Chebyshev distance is the minimum distance along any co-ordinate dimension (Aldenderfer and Blashfield, 1984; Field, 2005; Kaufman and Rousseeuw, 2005).

The linkage method determines how the start and end co-ordinates of the distance metric are defined. The single linkage method uses the shortest distance between the two elements in separate clusters. The complete linkage method uses the largest distance between two objects in different clusters. The average linkage method uses the average distance between all pairs of elements. The centroid linkage method uses the distance between the geometric centroids of the two clusters. The Ward Linkage method assigns elements to clusters by minimising the increase in the error sum of the Squared Euclidian distance. Therefore the Ward Linkage method is the most statistically efficient approach (Ward, 1963; Aldenderfer and Blashfield, 1984; Everitt *et al.*, 2001; Field, 2005; Székely and Rizzo, 2005; Mooi and Sarstedt, 2011).

2.11.3. Identifying the Number of Clusters within the Dataset

When conducting a hierarchical cluster analysis, the data are aggregated into a progressively smaller number of clusters. In order to conduct further analysis on a number of clusters, the researcher must select the number of clusters within the dataset to be further analysed. It is important to select the correct number of clusters. If too many clusters are specified, data that are not significantly different will be assigned to separate clusters. If too few clusters are specified, significantly different data could be merged into the same cluster (Wood *et al.*, 1996; Field, 2005).

One approach to determine the number of clusters is based on the Eigenvalue associated with the extraction of each factor. An Eigenvalue represents the variance within the dataset that can be accounted for by the extraction of an additional cluster. It has been suggested that all clusters with an Eigenvalue greater than 1.0 should be extracted. If an Eigenvalue is less than one, then this cluster explains less variance than the variance explained by the average variable (Kaiser, 1974).

Another approach is to use the Scree plot, which is a graphical illustration of the eigenvalues corresponding to the extraction of each additional cluster, allowing the relative importance of each cluster to be determined (Field, 2005). The number of clusters within the dataset can be determined by identifying the point of inflection on this Scree plot via visual inspection (Cattell, 1966). However, the inspection of a Scree plot does not always produce reliable results. This is because the identification of the point of inflection of a curve by the researcher is open to the interpretation (Cattell and Vogelmann, 1977; Gorsuch, 1983; Stevens, 1992).

In summary, Scree plots are a valid approach to determine the number of clusters. However, they can be considered open to researcher interpretation in some cases and as such as not as robust as the ‘Eigenvalue greater than one’. This is because this criterion provides a definitive rule for selecting the number of clusters that is not open to interpretation.

2.12. Identification of Key Themes from Focus Group Discussion and Written Driver Responses

2.12.1. Review of Methods of Focus Group Analysis

One key aim of this thesis is to identify the underlying causes of driver recharging behaviour. This is in order to understand how the current situation in the North East of England is impacting on recharging habits and to allow future policy, regarding recharging demand management, to be informed based on driver feedback. Information from focus groups, as well as written responses from drivers, was available for analysis. This section reviews the methodological approaches that are available for identifying key themes from these sources of data in order to inform the analytical approach to be adopted in this thesis.

Three methodological approaches were considered for the qualitative analysis of the focus group and interview discussions. These were Grounded Theory (GT), Interpretative Phenomenological Analysis (IPA) and Thematic Analysis (TA). GT is a methodology that aims to output a new behavioural theory. IPA and TA differ from GT in that they are both approaches that output patterns across the dataset, without aiming to generate behavioural theories. IPA is a methodological framework, in which the sampling method, the procedure used to collect data (qualitative interviews), how this data should be analysed and the interpretation of results are informed. TA is a procedure, rather than a methodological framework. TA can be applied to transcripts of data from focus groups, interviews and written communications such as email responses. This makes TA a more flexible approach (Braun and Clarke, 2006; Charmaz, 2006; Larkin *et al.*, 2006; Smith *et al.*, 2009; Birks and Mills, 2011; Guest *et al.*, 2011).

GT was rejected for use in this research as the aim of this research was not to develop behavioural theory. Instead, the aim is to capture information from discussions and written responses that can allow an understanding of driver recharging behaviour and the real world factors that influenced this. As such, GT is not further reviewed. TA and IPA both generate the outputs that are required. As IPA is a methodological approach, the researcher must be in a position to have control of the entire process from how the focus groups or interviews are to be conducted through to the final outputs. This was not the case in this research because the data available was collected as part of the wider SwitchEV project. Therefore, TA was the chosen method adopted for the research presented in this thesis. This is because TA provided a flexible method that could be applied to any relevant data that was made available for this study. The following section provides more detail.

2.12.2. Themes and Sub-Themes

TA outputs a set of unique themes and sub-themes (sometimes called 'organising themes' and 'basic themes') that together form a dataset relating to a wider global theme. A theme is *'something important about the data in relation to the research question, and represents some level of patterned response or meaning within the dataset'*. Each theme is comprised of a series of sub-themes, which are distinct yet reveal similar patterns. A series of similar themes describe an overarching global theme (Attride-Stirling, 2001; Braun and Clarke, 2006; Guest *et al.*, 2011). This is depicted in Figure 2-10.

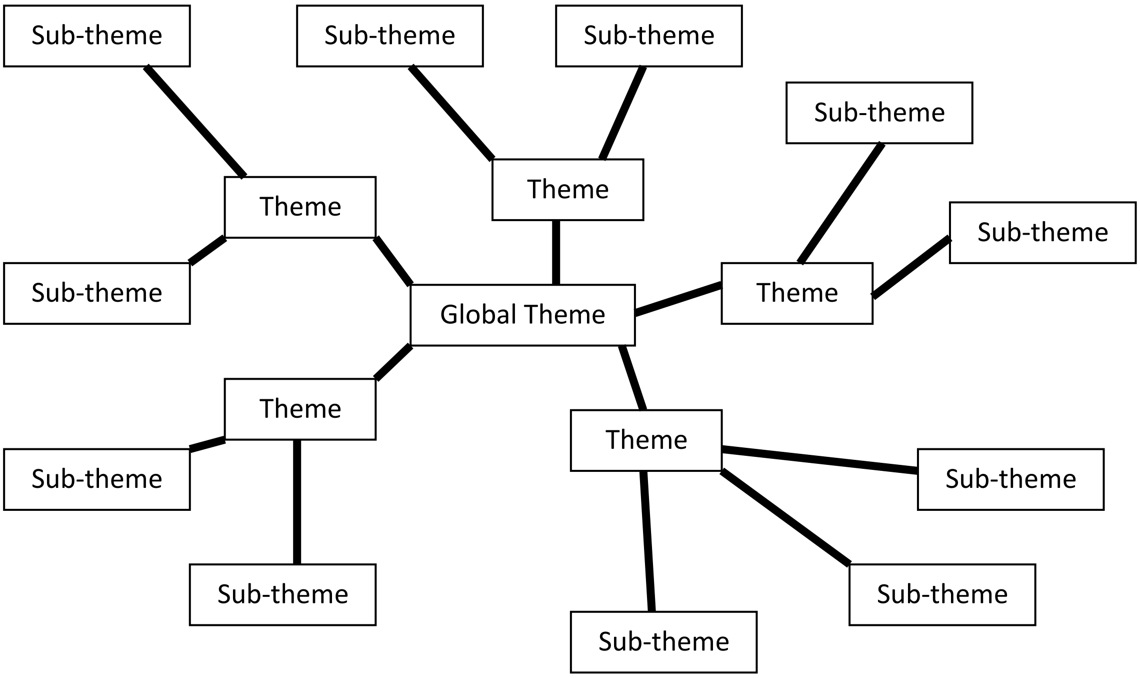

Figure 2-10: Levels of themes that can be identified through thematic analysis

The 'coding' process is the first stage of a thematic analysis. Basic themes consist of codes. A code is defined as '*the most basic element within the data that can be assessed in a meaningful way'.* Sub themes/basic themes consist of a number of codes that have been grouped together due to similarity (Boyatzis, 1998).

2.12.3. Inductive and Deductive Approaches to Theme Identification

There are two approaches that can be taken to identify themes; inductive and deductive. An inductive approach is where the researcher formulates no pre-existing plan as to how the data is to be coded or the type of themes that are to be identified. This is a data driven approach. A deductive approach is an analyst driven approach, whereby the researcher codes the transcripts of the focus groups and the written responses to questions based on their own interest in the area. The outputs of a deductive approach are not as rich as those of an inductive approach, but they provide a more detailed analysis of a particular aspect of the data (Boyatzis, 1998; Frith and Gleeson, 2004; Braun and Clarke, 2006; Guest *et al.*, 2011).

2.12.4. Quantitative Analysis of Themes

It has been argued that the importance of a theme can be quantified by measuring the prevalence of that theme across the dataset. An advantage of applying a quantitative approach is that the most commonly discussed themes are identified. However, it can be argued that this is not a reliable measure of importance. Not all relevant opinions and thoughts will necessarily be discussed by all participants in a focus group. Furthermore, the natural dynamics of the discussion may be guided by individuals away from topics that may otherwise have arisen. In addition, participants may be more inclined to discuss unimportant or trivial issues, giving the false impression that these are the most important. A problem this presents is that it is not possible to determine whether an issue is more or less important than others when counting themes as they can be guided by one individual. Therefore, quantitative analysis of themes can overemphasis particular themes, making them appear more important to the group as a whole than may be the case (Boyatzis, 1998; Pyett, 2003; Braun and Clarke, 2006; Guest *et al.*, 2011).

Attempting to quantitatively analyse themes relating to EV recharging infrastructure in order to try to identify the most common problems, issues and views of drivers could lead to an incorrect focus on policy that might not be beneficial to the group as a frequency count suggests. Therefore, this thesis does not attempt to quantitatively analyse themes.

2.13. Literature Review Summary

The need to make significant reductions in carbon emissions has seen the development of a policy environment that is favourable to the EV, including various government incentives. In order to facilitate growth in the EV market and to make the EV competitive with ICE powered equivalents, there is a consensus that a high density, non-domestic recharging infrastructure is required. Plans are in place for the development of these networks in the UK, the EU the US and China. However, there are two potential problems that arise from the development of these recharging infrastructure networks.

One is the risk of power grid overload. This is a problem with a localised element. The National Grid itself is not at risk. However, localised distribution networks are at risk if recharging occurs during periods of existing high demand. This will depend on the demand from other sources. Domestic demand peaks at the end of the working day, whereas business demand reduces in the evening. The other key issue is the carbon content of the power sources used to generate the electricity to recharge EVs. If low carbon electricity is not available when EVs are being recharged, the net environmental benefits of EVs will be reduced. Given that most power in the UK is generated and distributed nationally, rather than on a localised level, this has a national element that is not dependent on local conditions. This has created the need for technologies and policy that can manage recharging demand, ensuring that EVs are recharged during off-peak hours. In the UK, this is between midnight and 07:00hrs.

The technology proposed by the UK government to manage recharging demand is smart meters. These are devices which allow users to program a start time for EV recharging and can be combined with financial incentives, such as reduced off-peak electricity tariffs, in order to encourage drivers to utilize this functionality. Researchers have generated theoretical recharging demand profiles for EV users. There is a consensus that the policy of combining smart meters will be effective in reducing on-peak recharging demand.

The real-world CABLED and BMW MiniE trials in the UK found that smart meters and financial incentives were effective. However, these trials took place in regions with a relatively sparse non-domestic recharging infrastructure. There is currently no knowledge of how effective smart meters and financial incentives can be in a region with a high density, non-domestic recharging infrastructure with a membership access scheme. The implication of this is that the proposed government strategy for managing recharging demand has not been validated in a region with the density of recharging infrastructure in which EVs are likely to operate in future.

This research aimed to address this research gap, making use of both data collected from in-vehicle loggers and focus groups/questionnaires from the SwitchEV trials in North East England to quantify and understand the typical recharging behaviour of drivers. Furthermore, it was necessary to quantify the effectiveness of government policy regarding smart meters in a region with a high density of non-domestic recharging infrastructure with access via an annual membership fee and to understand how driver behaviour could be changed in future.

To be able to develop an effective and robust methodology, this required key literature to cover the following; how to identify subsets of data within a large dataset (in order to identify recharging profiles), best practice for implementing interventions and how to identify key themes of discussion within focus group and interview transcripts.

For identifying subsets of data, a review of multiple methods within the cluster analysis statistical technique was conducted. This is a data classification tool that identifies statistically similar subsets or groups within a large body of data. The advantage of using cluster analysis rather than splitting subsets of data based on researcher defined traits is that underlying constructs within the dataset are identified using this statistics driven approach, removing bias. There are two broad approaches; non-hierarchical is a top down approach whereby data begin in one cluster and are divided and hierarchical is a bottom-up approach whereby data begin as discrete points and are merged into progressively larger clusters, based on a distance metric. The hierarchical approach is the more robust, as it is not sensitive to randomly generated starting conditions. The most reliable distance metric is the ward linkage, as this method assigns elements to clusters by minimising the increase in the error sum of the Squared Euclidian distance. The most reliable method to identify the number of clusters within a dataset is to use the Eigenvalue greater than one rule, whereby all clusters with an Eigenvalue greater than one are extracted. This is because, unlike Scree plots, this method is not open to researcher interpretation.

When inviting potential participants to take part in interventions, they should only be given information that is relevant to them. Furthermore, this information should be framed in a positive way, to highlight the benefits of making a behavioural change, rather than focusing in negatives associated with continuing to behave in the same way.

Thematic analysis is the most appropriate tool for analysing focus group discussions and written feedback. There are three levels of theme; global themes, themes and sub-themes. The global theme is the highest level of theme; in the case of this research, factors influencing driver recharging behaviour. A theme is the next level below this, and constitutes something important and pertinent to the research question within the dataset. A theme can have several related sub-themes. Discussion unrelated to the global theme should be actively filtered by the researcher from the data, referred to as a inductive approach. This will remove discussion that is not pertinent to the aims of the research. A deductive approach is appropriate for all other discussion as it limits researcher bias. Themes should not be ranked qualitatively as this can give a false impression of the relative importance of a particular theme.

3. Methodology

3.1. Introduction

The aims of this research were to define the recharging demand profiles of a sample of EV drivers, to quantify the effectiveness of offering financial incentives as a demand management tool and understand the underlying factors that define driver recharging habits. This was to be determined in the context of a region with a high density recharging infrastructure network with membership scheme access to non-domestic recharging posts. This specific policy is being investigated in order to assess its suitability as a model for recharging infrastructure operations in future when there is likely to be more EVs on the road and greater demands on the network.

A key requirement of this research was access to trial data, including data from in-vehicle loggers in order to monitor driver recharging behaviours. Access to participants and to focus group discussions regarding EV recharging also was required, in order to understand why the EV driver recharging behaviour was as observed.

This research was conducted as part of the wider SwitchEV trial. This was a real world trial of EVs in the North East of England, between 2010 and 2013. There were four successive cohorts of users, each leasing the vehicle for approximately six months. The trial was managed and operated by the Switch EV consortium partners, with EV trips, recharging data and locations recorded using an in-vehicle logger and on-board GPS device. Newcastle University (NU) hosted computer servers into which binary data from in-vehicle loggers were collected. EV recharging data from in-vehicle loggers were made available for this thesis. Additionally, there was the opportunity to add EV recharging questions to the existing focus groups and transcripts were made available for analysis. This is illustrated in Figure 3-1.

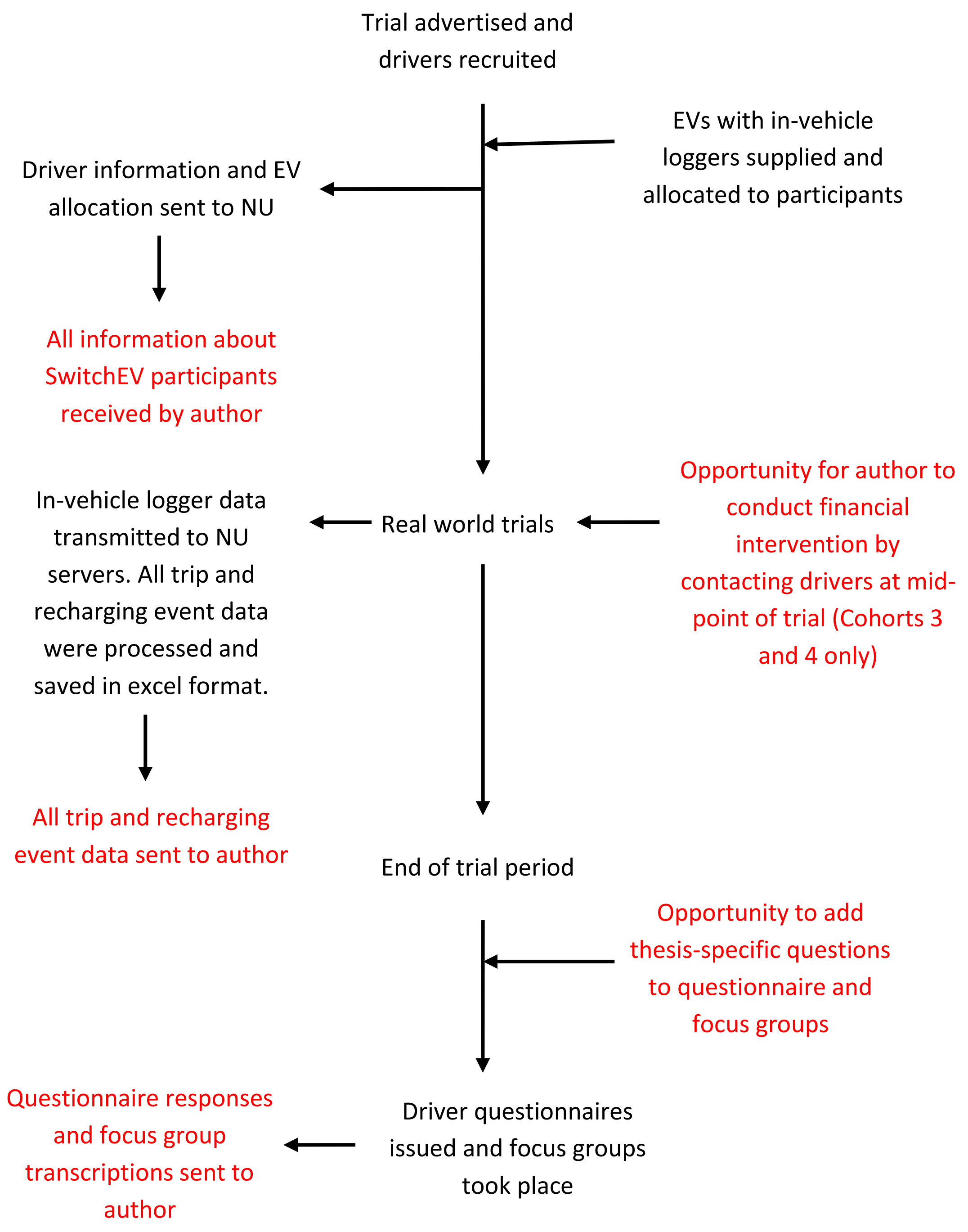

Figure 3-1: SwitchEV trial cohort flow chart and responsibilities (black text = SwitchEV consortium, including Newcastle University (NU) and red text = thesis author)

The first section of this methodology describes the work of the SwitchEV consortium members, as illustrated by the black text in Figure 3-1. This section describes the role of the SwitchEV project consortium partners, the EV technical specifications, the installation of recharging infrastructure, the recruitment of participants and the trial periods, the technical specifications of the in-vehicle data loggers, how the logger data was collected and processed and the availability of recharging data for use in this research. This section also describes the driver questionnaires and the collection of data from focus groups and interviews. All work described in this section was completed by the consortium partners and not as part of this thesis. However, it is relevant as data used in the study was derived from these activities and processes. All other sections of the methodology describe work undertaken by the author as part of this thesis.

When these data were available, the next stage was to analyse this data in order to define the recharging demand profiles of EV drivers. Part two of this section describes how these EV recharging data was processed in order to identify the typical recharging demand profiles within the dataset and how the soft data from focus groups, questionnaires and written responses were analysed to identify key themes of discussion relating to EV recharging behaviour. This includes the processing of raw data to form the recharging profiles, the generation and application of carbon content of electricity curves to the EV recharging data, the application of cluster analysis to identify “typical” recharging profiles and the post-clustering analysis. This section also describes the analysis of the focus group discussion.

Part three describes the design, implementation and analysis of the intervention. This includes the design of the intervention, the driver recruitment process, the selection of the control group of users and how behavioural changes were quantified. In addition, the questions to which intervention participants were asked to respond once their trial period was completed are detailed.

3.2. Methodology Part One: SwitchEV Consortium

3.2.1. Introduction

The SwitchEV trials took place in North East England between September 2010 and May 2013. The SwitchEV consortium members were; the technology Strategy Board (TSB), Future Transport Systems (FTS), Newcastle University, Nissan, Peugeot, Liberty Electric, Avid and NE PiP.

The SwitchEV project was managed by FTS. Their role included the recruitment of drivers for the trials, the management of the trials and vehicles and contract management.

Newcastle University were responsible for the collection of hard (technical) data from vehicle loggers, generating TSB-prescribed data outputs (see data collection and processing section), the organisation and transcription of focus groups, data analysis and conducting any other relevant studies and research with consortium permission. Nissan, Peugeot, Liberty Electric and Avid were responsible for providing vehicles. Characteristics of the vehicles utilised in the SwitchEV project can be seen in Table 3-1.

Vehicle	LEAF	iOn	Cue-V	E-Range	Edison
Manufacturer	Nissan	Peugeot	Avid	Liberty Electric Cars	Smith Electric Vehicles
Stated range (Miles)	109	93	80	200	70
Recharging time at 230V (hours)	8	7	7	10	8
Battery capacity (kWh)	24	16	18	75	51
Number of vehicles in the trial	15	20	6	2	1

Table 3-1: *SwitchEV trial vehicle performance specification*

As observed in Table 3-1, there were 44 EVs involved in the SwitchEV trial in total. Only data from users leasing the Nissan LEAF and Peugeot iOn vehicles were made available for the analysis in this thesis. This was for two reasons. Firstly, they were the only commercially available vehicles involved in the project, and therefore will provide evidence of how real EVs will be used in future. Secondly, the in-vehicle data-loggers (see ‘hard data collection and processing’ section) for the other vehicles did not perform reliably.

The NE PiP team were responsible for installing recharging infrastructure across the North East of England region. Although a separate project, NE PiP worked with the SwitchEV consortium to ensure that all drivers in the trial had access to a recharging solution (see ‘driver recruitment’ and ‘study area and installation of recharging infrastructure’ sections).

3.2.2. Study Area and Installation of EV Recharging Infrastructure

The SwitchEV trial was implemented in conjunction with the NE PiP scheme, which began in April 2010. Funding was made available for the installation of recharging infrastructure at private homes, as well as on-street, in public car parks, at workplaces and at commercial locations. Private EV owners and those with business access to an EV could have a home recharging point installed with NE PiP funds contributing 100% of the equipment and installation costs. Flexible funding arrangements were available for the installation of recharging infrastructure for organisations and local authorities, with NE PiP contributing between 50-100% of the equipment and installation cost on a case-by-case basis.

3.2.3. Driver Recruitment and Trial Management

Future Transport Systems (FTS) were responsible for driver recruitment and trial management. The vehicles were leased to a private individual or organisation, for a fee of £221/month over a six month trial period. There were three types of SwitchEV user;

- Private user – a member of the public paying the lease cost for personal use of the EV
- Organisation Individual (Org Ind) – an organisation paying the lease fee for an EV to be used by one member of staff
- Organisation Pool (Org Pool)-an organisation paying the lease fee for an EV to be used as a pool vehicle by more than one member of staff

The opportunity to take part in the trial was advertised in local press and on the Switch EV and FTS website. Interested parties were then asked to complete a questionnaire to assess their suitability to take part in the trials. There were separate questionnaires for individual drivers and for organisations considering participation in the trial. The aim of these questionnaires was to determine whether drivers met both necessary and desired criteria as agreed by the Switch EV consortium.

Once the deadline for applications had passed, all completed applications that had been submitted were reviewed to ensure that they met the minimum requirements, as agreed by the consortium.

The minimum requirements for Private users were:

- Hold a full UK driving license.
- Homeowner and be willing to have a NE PiP recharging point installed at home.
- Access to off street parking.
- Have home and fire insurance.
- Willing to have EV usage tracked by a GPS device and in-vehicle logger.

For both types of organisation users, the following necessary criteria were used:

- Hold a full UK driving license.
- Requirement for a recharging solution.
- Willing to have the vehicle tracked by GPS/vehicle loggers (see section on this for more detail).

All applicants were then subjectively selected by FTS based on the following criteria:

- Range of expected mileage.
- Proximity of base (home or work) to urban centres.
- Characteristics of early adopters.
- Media friendly.
- Easy to work with.

There were four lease periods, each lasting approximately six months. Data collected in each period was referred to as ‘Cohort 1, Cohort 2, Cohort 3 and Cohort 4’. The approximate start and end dates for these cohorts are shown in Table 3-2.

Cohort Number	**Start month**	**End month**
1	March/April 2011	September/Oct 2011
2	September/Oct 2011	March/April 2012
3	March/April 2012	September/Oct 2012
4	September/Oct 2012	March/April 2013

Table 3-2: Switch EV user cohort start and end months.

3.2.4. Hard Data Collection and Processing

Each Switch EV vehicle was fitted with a data logger. Vehicles were fitted with data loggers with the following features:

- Built-in GPS device and GPRS Modem to transmit data.
- 16 or 32MB on-board fast serial memory.
- Host and client USB interfaces.
- Secure Digital (SD) Card interface.
- Dual Controlled Area Network (CAN) physical vehicle interface.
- Fault Tolerant CAN physical vehicle interface.
- Physical vehicle interface in accordance with ISO9141 ‘Road vehicles - Diagnostic systems - Requirements for interchange of digital information’.
- FEPs programming voltage.
- Programmable multiplexing of J1962 (diagnostic connector) pins.
- 4 Port digital Input / Output interface.
- 8 Port analogue input interface.
- Battery backed Real-time Clock (RTC).
- Internal buzzer/sounder.
- Remote LCD POD interface (or 10 DIO interface).
- Low power sleep mode (4mA).

It can be seen that the loggers recorded data at a frequency of 1Hz. Data were collected from the vehicle CAN bus. The logger was designed to record both analogue and digital external inputs. The CAN bus data was overlaid with measurements from an external timer and GPS device also situated inside the vehicle.

These measurements included an instantaneous measurement of the following key parameters every second:

- Time – taken from the external GPS device.
- GPS co-ordinates (latitude, longitude, altitude) – taken from the external GPS device.
- Vehicle speed (Peugeot iOn only, read from vehicle odometer).
- Battery current (A).
- Battery voltage (V).
- Temperature (^{0}C).
- Ignition on/off.

Initially, these data were stored on the loggers' hard drive within the vehicle. They were then transmitted via GPS to a University server in a binary format. Initially the following parameters were calculated for each trip and recharging event:

- Vehicle data logger number.
- Start time of trip (defined at the point when the vehicle ignition was switched on).
- End time of trip (defined at the point when the vehicle ignition was switched off).
- Start time of recharging event (defined at the point when the transfer of electricity into the vehicle battery started).
- End time of recharging event (defined at the point when the transfer of electricity into the vehicle battery stopped).
- Energy used per second during trip (this was determined by multiplying the current by the voltage to calculate the energy used per second).

- Energy transferred recharging per second (this was determined by multiplying the current by the voltage to calculate the energy used per second).
- Speed (for Peugeot vehicles only this was read from vehicle odometer).
- Vehicle position (from GPS).

From this information, the following parameters were then calculated:

- Duration of trip (End time of trip-Start time of trip).
- Duration of recharge (End time of recharge-Start time of recharge).
- Total energy used per trip (A summation of all individual energy used calculations over the duration of the trip).
- Total energy transferred during recharge (A summation of all calculated individual energy transferred calculations per second over the duration of the recharging event).

The location was defined for each of the recharging events. The distance between the GPS position of the EV and the known GPS position of the recharging infrastructure was calculated.

The following definitions were used for recharging locations:

- Home – a NE PiP domestic recharging post. All recharging events taking place at a home address were classified as home regardless of which user was recharging at home.
- Public – a NE PiP recharging post at a public location (shopping centre, on street, public car park).
- Work – a NE PiP recharging post at a corporate location or local authority staff car park. If a user was making use of a work recharging post that was not located at their workplace then this was classified as Public.
- Fast – a 50kV fast recharging station within the NE PiP network.
- Other – A recharging event that did not occur at a NE PiP post.

It should be noted that the data made available and used within this research covers periods of time including weekends, weekdays, bank holidays and any periods where participants might be taking leave from work.

3.2.5. Soft Data Collection

There were two types of soft data collected as part of the SwitchEV trial. The first was the responses of participants to both pre and post-trial questionnaires. The second was a series of focus groups and driver interviews.
Agreement to complete both questionnaires was part of the contract for users participating in SwitchEV. Drivers were sent a link, via email, to the pre-delivery questionnaire approximately one week before their vehicle was delivered. Drivers were invited to complete the post-trial questionnaire one week after their lease had expired.

The pre-delivery questionnaire was sent to all drivers once they had agreed to participate in the trial. Questions aimed to understand the following:

- Driver demographics (age, gender, employment status and annual income).
- Reasons for participating in the trial.
- Current vehicle access and driving habits.
- Pre-trial attitudes and perceptions regarding electric vehicles.
- Expectations of EV performance.

The post-trial questionnaire, sent to all drivers on completion of their trial period, aimed to understand the following questions regarding EV recharging:

- Post-trial attitude to electric vehicle performance.
- Attitudes to EV recharging.

Focus groups and interviews involved between one and eight SwitchEV participants. Due to time constraints of participants, there was no gender bias in the recruitment process. Drivers were invited to take part via email. There were 14 focus groups and interviews in total. The frequency of these, for each number of participants, can be seen in Table 3-3.

Number of participants in interview/focus groups	Number of groups
8	1
7	3
5	1
4	3
3	3
2	2
1	1

Table 3-3: Number of focus groups and participants

The discussions were semi-structured. Drivers were asked to discuss the following topics, consistent with those identified as important by and of interest to both academics and the SwitchEV consortium industrial members:

- Perceptions of EVs both before and after the trial.
- Changes in driving behaviour during the trial period.
- Barriers to EV driving.
- Use of in-car technologies (e.g. satnav, heater).
- Recharging behaviour.

Responses to the following questions in this area were of particular interest:

- When and where did you have access to recharging infrastructure?
- When and where did you recharge your vehicle?
- Why did you recharge in these locations?
- Did the unlimited parking and electricity influence recharging behaviour?
- Are there any locations that you feel require or need more recharging posts?

Discussion relating to these questions was considered for further analysis because one of the aims of the thesis was to understand how drivers were using the infrastructure in order to ensure that the future policy recommendations regarding recharging demand management that result from this research are informed by user feedback.

3.3. Data Processing and Identification of Typical Recharging Profiles

One of the aims of this research was to define the recharging demand profiles that can be observed within a region with a high density recharging infrastructure and a membership access scheme. This section describes the analytical techniques that were used in order to classify typical recharging profiles for all users. Also it describes the statistical approaches undertaken in order to identify any differences depending on the user type and recharging location be in the recharging profiles. These factors are investigated further because the literature suggested that they could influence recharging profiles. There are some statistical methods that were repeated throughout this research. These methods are described in detail below. For all statistical analysis undertaken in this thesis, the confidence level for statistical significance was 95%.

The centrality measure of distributions was required throughout the analysis. Initially, a Shapiro-Wilk test was used to test the normality of the dataset. If the distribution of data were normal (parametric), the mean value was used as the centrality measure. If the data was not normal (non-parametric), then the median was used. When testing whether the centrality measure of a distribution differed significantly from zero, T-tests were used for parametric distributions and Wilcoxon Signed Rank tests were used for non-parametric distributions.

When analysing whether recharging profiles were significantly correlated, the Pearson correlation co-efficient was used. This tests whether there was a linear relationship between the two recharging profiles.

3.3.1. Identification of Recharging Profiles

The in-vehicle loggers and GPS devices provided information regarding the vehicle logger IDs, the GPS locations and the start and end times of the recharging events. Before any research was undertaken regarding defining the recharging profiles some further additions were made to the TSB data file.

The first stage was to assign a unique user ID to each recharging event in the TSB data file. This was to allow the driver/user to be identified. This was necessary because drivers/users in each cohort would share vehicle logger ID numbers. User data was stored securely and was password protected. No names or addresses of users were made available outside of the SwitchEV consortium partners.

The profiles were based on the total amount of recharging in each hourly interval of the day for all days during the vehicle leasing period. This approach is consistent with the approach adopted by other researchers in this field (Morrow *et al.*, 2008; Kang and Recker, 2009; Jansen *et al.*, 2010; Axsen *et al.*, 2011; BMW Group, 2011; Camus *et al.*, 2011; Everett *et al.*, 2011; Wang *et al.*, 2011; Camus and Farias, 2012).

A frequency count of ‘1’ was assigned if a recharging event was taking place at any point within a given hour. For example if an event started at 12:10 and finished at 02:15h a frequency of ‘1’ was added to the 12:00h – 01:00h, 01:00h – 02:00h and 02:00h – 03:00h. A ‘0’ was added to all other hours. Therefore, a value of 1 in any given hour does not necessarily represent a full hour of recharging. It indicates that some recharging, potentially an hour but not necessarily so, occurred within this hourly interval.

3.3.2. Calculating the Carbon Content of Electricity Associated with EV Recharging

The carbon content of electricity over a 24 hour period was calculated using the approach described by Kemp *et al.* (2010) and McCarthy and Yang (2010). This method requires power generation data, a power transmission loss factor and emissions factors for the carbon content of power generation for each power source used to generate the electricity, which changes throughout the day.

Typical UK summer and winter electricity generation data at half hourly intervals were obtained from National Grid (2011b). Each half hourly generation level is based on the sum of the total output from the eight energy generation sources. These were coal, natural gas, nuclear, imports, oil and open cycle gas turbine (OCGT), pumped storage, hydro and wind. The average carbon emissions factors for power generation and power transmission loss factor for the period 01/04/2012 – 31/03/2013 were obtained from the Department of Energy and Climate Change (2013b). Table 3-4 illustrates the carbon emissions factors for power generation. The power transmission loss factor was quoted as 1.10.

Source	**CO_2 Content (gCO_2/kWh)**
Nuclear	0
Coal	910
Gas	390
Other	590
Renewables	0

Table 3-4: Carbon content of electricity generation in the UK by power source (Department of Energy and Climate Change, 2013b)

For each half hourly interval, the carbon content of electricity in summer was calculated. The emissions factor for coal was multiplied by the total 'typical' summer energy generation from coal in this time interval. This gave the total emissions from coal. This process was repeated for the other seven power sources. Not all sources of power generation have their emissions quoted. Wind and hydro were classified as renewable. Oil and OCGT, imports and pumped storage were classified as 'other'.

The sum of these eight emissions totals for each power source gave the total for each half hour of the day. This was then divided by the total output to give the average emissions in this half hourly interval. This process was repeated for each half hourly interval throughout the day to give a typical carbon content of electricity profile across a 24-hour period separate for summer and winter thus allowing the impact of recharging behaviour on carbon emissions to be compared irrespective of day to day fluctuations in power demand. The summer and winter average carbon content of electricity profiles can be seen in Figure 3-2.

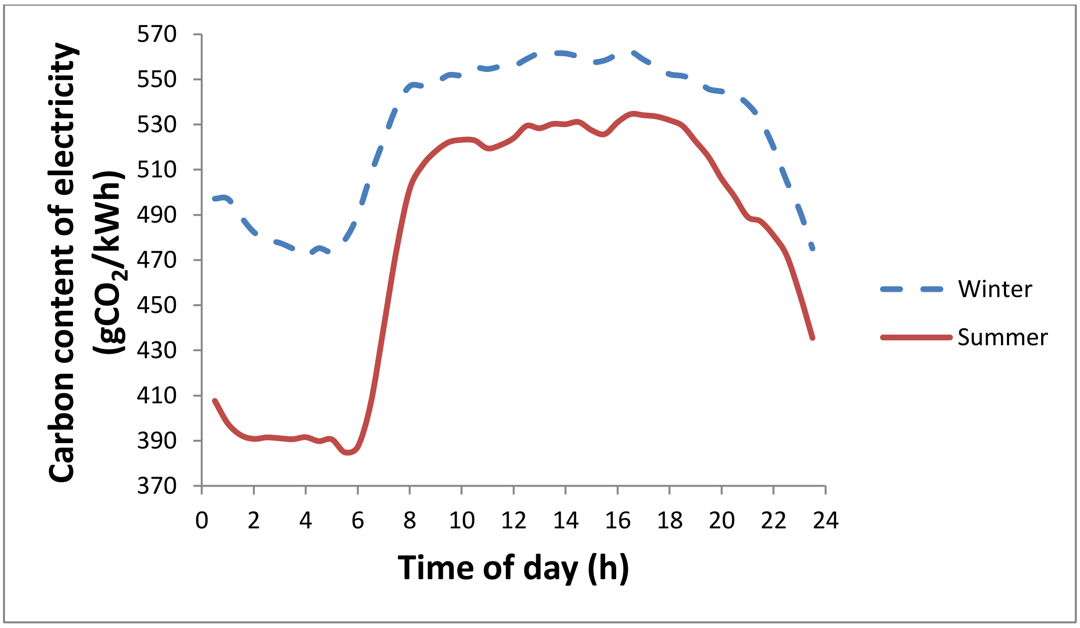

Figure 3-2: Seasonal carbon content of electricity in the UK by time of day

For each recharging event the proportion of recharging time within each half hourly interval was multiplied by the carbon content of electricity within the half hourly period.

Where recharging events occurred throughout the interval, the average of the carbon content at the start and the end of the interval was used. If a recharging event occurred in part of an individual interval, the carbon content was scaled assuming a linear increase or decrease between the start and end of the interval. The average carbon content was then based on the scaled value(s). For example, the carbon content of electricity is 473.6gCO_2/kWh at 05:00h and 478.8gCO_2/kWh at 05:30h on a typical winter day. If an EV was recharging between 18:00h and 18:30h, the average carbon content for this half hour would be;

$$\frac{gCO2}{kWh} = 0.5 \times (473.6 + 478.8) = 476.2$$

If an EV recharging event took place between 05:18h and 05:30h, the average carbon content at 05:18 would be;

$$\frac{gCO2}{kWh} = 473.6 + \left(\lfloor(478.8 - 473.6)\rfloor \times \left\lfloor\frac{0.3}{0.5}\right\rfloor\right) = 476.7$$

The average CO_2/kWh for this 12 minute interval would be;

$$\frac{gCO2}{kWh} = 0.5 \times (476.7 + 478.8) = 477.8$$

This method is effectively calculating the carbon content of electricity over a given duration based on exact start and finish times.

3.3.3. Cluster Analysis

The first stage of a hierarchical cluster analysis is to quantify the number of clusters present within the data. This was identified through the Eigenvalue associated with the amount of variance that can be explained by the extraction of each additional component (recharging profile). Eigenvalues were quantified for the 24 normalised frequency counts across all users. This was to allow the variability in recharging demand peaks by time of day for EV drivers to be determined.

Two approaches were adopted for identifying whether a component had a significant Eigenvalue to justify extraction for the cluster analysis. The first approach used the Kaiser method to determine an alternative measure for the number of clusters. In this method all recharging profiles with an Eigenvalue of 1.00 or above were retained (Kaiser, 1974).

The second approach was to generate a Scree plot for the 24 normalised frequency counts for all users. This approach allowed the number of Eigenvalues to be determined by identifying the point of inflection at which further clusters do not substantially improve the performance of the model (Eigenvalue) that is consistent with previous researchers.

If there was disagreement between the number of clusters identified by the two approaches, the Eigenvalue greater than one rule was used. This is because this method is not subject to researcher interpretation. A hierarchical cluster analysis was then conducted on the data, using the number of clusters identified using the Kaiser rule. The chosen linkage method was Ward linkage. The distance metric was the squared Euclidian distance. The 24 recharging by time of day frequency counts for each user were normalised. This was to ensure that the shapes of the profiles were being compared to one another in terms of relative usage by time of day and not the magnitude of the energy used in recharging. 24 frequency counts were the inputs into the cluster analysis.

In order to understand the impact and implications of selecting a specific number of clusters, the clustering of recharging profiles was repeated with one more and one less cluster in addition to the selected number of clusters. The movement of users between profile groups for the three clustering solutions was investigated.

3.3.4. Analysis of Cluster Allocation

In order to analyse the impact of user characteristics on the recharging profiles, a Chi-squared analysis was undertaken. The inputs were the number of users within each profile. The first stage was to test whether the total numbers of each user type were distributed evenly across the recharging profiles that were identified. The second stage was to determine whether there was a statistically significant difference in recharging profile allocation between each of the three user types. These tests were undertaken because literature suggested that user type could influence recharging demand. This is important because, depending on to whom EV sales are made in future, recharging demands could differ and thus alter the necessary policy requirements to ensure recharging can be managed effectively and determine whether investments in power distribution network strengthening is required.

Chi-squared analysis was used for these tests. When undertaking Chi-squared tests, all frequency counts were required to be greater than or equal to five. If this criterion was not satisfied, cells were merged until the expected frequency counts were above five. There is no common rule for merging cells (it can be either the smallest groups or groups with a logical link). Therefore, the merging process was justified on a case by case basis. This process was repeated until the expected cell counts were all above five. If the contingency table reached the point of having one degree of freedom and the expected cell counts were still below five, a Fisher Exact test was used instead of Chi-squared. This test can only be applied to contingency tables with one degree of freedom but is more robust than Chi-squared when expected frequency counts are below five.

3.3.5. Further Analysis of Driver Behaviour within Clusters

For each of the overall recharging profiles, the recharging demand by location was compared between the each of the three pairs of user types using the Pearson correlation coefficient. This was to test for a linear correlation between the user types. This test was undertaken because it will inform policymakers of whether the user group demand profiles are a function of the recharging infrastructure location types (home, work public or other) and time of day. This is important to understand because it will determine whether recharging profiles can be influenced by the same policies or whether multiple management strategies might be required for different users with the same recharging demand profile. The Pearson correlation coefficient also was calculated to compare recharging demand profiles by location between the different recharging demand profiles. This test was undertaken in order to ascertain whether users in different groups/clusters use recharging infrastructure at specific locations in the same way.

3.4. Design, Implementation and Analysis of the Intervention Process

3.4.1. Incentives and Driver Recruitment

The intervention process was aiming to test the effectiveness of offering information and financial incentives to encourage drivers to recharge their vehicles during the low carbon off-peak period. Off-peak hours were defined as between 24:00h and 07:00h in this study. This was selected to coincide with the standard industry definition (British Gas, 2013; EDF Energy, 2013; Energy Choices, 2013).

Half of the SwitchEV participants were sent an email at the mid-point of their trial period, offering them a reimbursement of 50% of the cost of an average unit of electricity used to recharge their EV for the entire recorded duration during the off-peak period. The target was to recruit half of each of the three user types for the intervention. Drivers were chosen from each user type using a random number generator. Once chosen, they were sent an email inviting them to take part in the trial. A response to the email accepting the invitation verified that a user was taking part in the study.

If the initial randomly selected users did not respond within one week, it was assumed that they were not interested. At this stage other users of the same user type were randomly selected and invited to take part until either half of the total number of each user type were invited or if all drivers had been invited.

The email to the drivers was designed using the following criteria:

- Inform the driver of positive environmental benefits due to a change in behaviour. The literature suggested that highlighting the positive benefit of making a behavioural change is more effective than highlighting the negatives associated with not making a behavioural change.
- Explain the behavioural change that is being sought. This was to ensure that drivers were fully aware of the requirements and to prevent the results potentially being indicative of a lack of understanding of the intervention rather than driver ability and/or willingness to change behaviour.
- Provide practical and relevant advice to drivers regarding how they can change behaviour if they choose to do so. This was informed by the literature suggesting that advice should be tailored to specific users.
- Information to be simple and informative.

The email sent to drivers included the following:

‘For the remainder of your trial period, you are eligible to be reimbursed the value of some of the electricity you use to recharge your vehicle. If you wish to participate in this electricity reimbursement study please respond to this email. This reimbursement study is led by the Transport Operations Research Group at Newcastle University, as part of our analysis of the electricity demand placed on the power grid by electric vehicles. Due to the way power is generated in the

UK, electricity has approximately 20% less carbon per unit during the night than during the daytime peak. Therefore, your recharging habits can impact on how 'green' your trips are.
If you agree to take part, you will be reimbursed 50% of the value of all the electricity you have used when recharging between midnight and 07:00am'

Drivers were then provided with a table quoting the carbon saving and financial reimbursement for a 25%, 50%, 75% and 100% battery recharge during the off-peak hours. This was implemented to compensate for the lack of a feedback mechanism in this research, due to SwitchEV consortium requirements. By providing this information, drivers were made aware of both the financial and environmental impact of their behaviour and could refer back to the email if necessary.

Additionally, EV users were provided with contact details to both respond to the request to take part and to allow them to ask any further questions or clarify anything they did not understand.

3.4.2. Selection of Control Group

Users who agreed to participate in the intervention process were classified using the following characteristics;

- Pre-intervention recharging profile.
- User type/group.
- Whether they had access to home recharging infrastructure.

Subsequently these were compared to the classifications of users taking part in the interventions. The number of users selected for the control group from each of the classifications was determined as follows;

- If there were more non-intervention participants of a particular classification than there were intervention participants, then a randomly selected sub-set of users were chosen from the group of non-intervention participants such that the control group and intervention group had the same number of users of the same classification. This was to ensure that users in the control group were representative of the group of intervention participants.

- If there were the same number of users in the valid non-intervention participant group and the intervention group, all of the valid non-intervention participants were selected to be part of the control group.
- If there were fewer valid non-intervention participants of the same classification than there were in the intervention group, all valid non-intervention participants were selected. Additional, valid non-intervention participants were selected from the closest group, such that the recharging profile that had the closest peak demand to the user classification being considered. Therefore, within this closest group, a user with the same home recharging provision was selected.

If the number of users in the intervention group did not match the control group, then the Chi-squared test procedure was used to prove, to a 95% level of confidence, that the intervention group and the control group were not significantly different in terms of user type representation from each pre-intervention recharging profile.

3.4.3. Analysis of Interventions

The objective of this analysis was to understand whether SwitchEV users participating in interventions made a statistically significant change to their recharging behaviour, both in terms of the amount of recharging taking place off-peak and in respect of the usage of recharging infrastructure by location. The behaviour of a representative control group was quantified also in order to determine whether or not changes in recharging patterns of intervention participants were mirrored by changes in the control group. This will determine whether behavioural changes can be attributed to the intervention.

For all users, both in the control and in the intervention group, the recharging event data were split into pre and post intervention periods. For users not taking part in the interventions, an equivalent pre/post-intervention period of time was required. The number of days into which control group driver data were considered to be pre-intervention was defined as centrality measure of the distribution of the number of days into the trial period that the post-intervention period commenced for intervention participants. This was to ensure that recharging behaviour was being compared over an equivalent period of time. This was confirmed using a two stage process:

- A Sharipo-Wilk test was conducted on the distribution of the number of days into the trial period after which the post-intervention period commenced for intervention participants. This was to determine whether the data were normally distributed.
- If the data were normal, the median value defined the number of days into the trial in which the post-intervention period for non-intervention participants begins. If data were not normal, the median value was used. This is because non-normal data can have a mean that is skewed.

For pre-intervention and post-intervention data for each user, the following were calculated;

1) The difference, in percentage points, of the total frequency of off-peak recharging that took place during the off-peak hours. This was based on the total frequency count for all recharging events between 00:00h and 07:00h being divided by the total frequency count for all 24 hours of the day. The percentage point difference in off-peak recharging was calculated by subtracting the percentage of off-peak recharging for all recharging events before the intervention from the percentage of off-peak recharging for all recharging events after the intervention.

For example: A driver completes 100 hours of recharging pre-intervention, of which 5 were recorded during the off-peak hours. The percentage of pre-intervention recharging was 5%. If this same driver completes 120 hours of post-intervention recharging, of which 18 hours were off-peak, the post-intervention off-peak recharging was 15%. Therefore, the percentage point change in off-peak recharging during the off-peak hours is 15%-5% = 10%.

2) For each location, the percentage of the total recharging frequency that took place during the off-peak hours was also calculated. The total frequency counts between 00:00h and 07:00h for a location were divided by the total frequency count for all hours at that location to calculate the percentage of off-peak recharging. The percentage point difference for each location was then calculated by subtracting the percentage of off-peak recharging during the pre-intervention period from the percentage of off-peak recharging during the post-intervention period.

For example: A driver completes 100 hours of pre-intervention recharging, of which 60 hours take place at home. Of these 60 hours, 5 hours are recorded during the off-peak period. Therefore, the percentage of off-peak recharging is 8.3% during the pre-intervention period. This same driver completed 90 hours of post-intervention recharging, of which 25 hours are recorded off-peak. The post intervention proportion of off-peak recharging is 27.8%. Thus, the post-intervention percentage point change in off-peak recharging would be 19.5% at home. This process would then be repeated for all locations.

3) The proportional change in carbon content of electricity before and after the intervention was calculated. The carbon content of electricity was divided into five groups. The smallest group was starting with greater than or equal to 350gCO_2/kWh and less then 400gCO_2/kWh. Subsequent groups increased the upper and lower bound by 50gCO_2/kWh. The percentage of the total number of recharging events within each carbon content group was then calculated, when both the winter and summer carbon content of electricity profiles were calculated. The percentage point difference for each interval was calculated by subtracting the pre-intervention percentage of recharging in each interval from the post-intervention percentage of recharging events for each carbon interval.

For example: A driver records 80 hours of pre-intervention recharging in which four recharging events of 3, 4, 3 and 2 hour durations have an average carbon content during the event that is in the 350-400gCO_2/kWh range. The total recharging time of recharging events in this range is therefore 12 hours, which is 15.0% of the total. This driver then records 90 hours of post-intervention recharging, of which eight events of duration 3, 4, 4, 5, 3, 3, 4 and 3 occur *during the off-peak hours. This totals 30 hours where the average carbon content of recharging was in this bracket, and accounted for 33.3% of recharging. Therefore, the post-intervention percentage point change in the amount of recharging taking place in this bracket is 18.3%.*

4) The post-intervention recharging events were categorised according to the number of months after the day of the intervention that they occurred. For simplicity the analysis was carried out in 4-weekly periods. Therefore, a month was defined as a 28 day period i.e. month 1 consisted of all recharging events that occurred within the first 28 days after the day that the user agreed to take part in the intervention. This approach was adopted to keep the number of days per 'month' consistent. The proportion of off-peak recharging in month 1 was calculated as the total number of times recharging occurred between 00:00h and 07:00h for all recharging events divided by the total number of times recharging occurred during all 24 hour daily intervals for all recharging events in month 1. For this calculation, the difference in percentage points for each month was compared to the total percentage of off-peak recharging for all pre-intervention data to determine whether there was a change in behaviour in each month relative to the overall pre-intervention period. For each month, the percentage point difference in off-peak recharging compared to the pre-intervention recharging behaviour was calculated by subtracting the percentage of off-peak recharging for all pre-intervention recharging events from the percentage of off-peak recharging within each individual month.

For example: A driver completes 90 hours of pre-intervention recharging, of which 20 hours (22.2%) occur off-peak. In the three months following the intervention, the driver completes 22 hours, 30 hours, and 25 hours of recharging, with 5, 14 and 13 hours respectively occurring during the off-peak periods. Therefore, the percentage of off-peak recharging following the intervention was 22.7%, 46.7% and 52.0% respectively for post-intervention months 1, 2 and 3. Therefore, the percentage point change in off-peak recharging relative to the pre-intervention period were 0.5%, 24.5% and 29.8% respectively for post-intervention months 1, 2 and 3.

3.4.4. Assessment of Behavioural Change

For the control group users, the distribution of percentage point differences for each user was tested for normality using a Shapiro-Wilk test. The null hypothesis was that there was no change in behaviour in the control group between the pre and post-intervention period. This was tested by applying either a T-test (for normally distributed data) or a Wilcoxon Signed Rank test (not normally distributed data) to the distribution of percentage point changes before and after the intervention per user, to determine whether the centrality measure was statistically significantly different from zero at a 95% level of confidence.

The distribution of percentage point changes for the intervention participants were then tested in the same way for the post-intervention data. If there was no significant change in the pre-and post-intervention period for the control group, the null hypothesis remained that there was no change in behaviour for the intervention participants. If there was a significant change in behaviour for the control group, then the null hypothesis for the intervention group was that there was no difference in behaviour between the centrality measure of the non-intervention participants and the intervention participants. The centrality measure of the distribution of intervention participants was tested to determine whether it was statistically significantly different from the non-intervention participant centrality measure at a 95% level of confidence.

This process was applied to the following percentage point change distributions;

- Duration of off-peak recharging for all users.
- Carbon content of electricity during EV recharging, when both winter and summer recharging profiles are applied to recharging data, for all users.
- Duration of off-peak recharging for all users at fast, home, work, public and other locations.
- Duration of off-peak recharging at home only for users with access to home recharging infrastructure.
- Duration of off-peak recharging at work only for users with access to work recharging infrastructure.

- Percentage point change in recharging in post-intervention months 1, 2 and 3 for all users.

3.4.5. Testing the Relationship Between Response to Intervention and Total User Recharging duration

The relationship between the post-intervention recharging duration and the percentage change in off-peak recharging was tested. This was to determine whether there was a statistically significant relationship between the total number of hours of recharging recorded by a user and the percentage point change in their recharging behaviour between the pre-and post-intervention time periods. It was important to understand this because, if the intervention was only successful in changing the behaviour of those who already place minimal recharging demand on the power distribution network, the additional measures might be required in future. The strength of the relationship was assessed using the Pearson Correlation coefficient for the relationship between the total duration of recharging during the post-intervention period and the percentage point change in off-peak recharging. This was calculated for all intervention participants as a whole, and separately for each user type.

3.4.6. Feedback from Intervention Participants

It was important to understand whether the drivers were motivated by the financial incentive. Therefore, how difficult it was for the participants taking part in this intervention to change their recharging behaviour, and whether there were any perceived or actual barriers to behavioural change (Satoshi, 2006; Abrahamse *et al.*, 2007; Chatterton *et al.*, 2009; Whitmarsh, 2009) needed to be investigated. Therefore, the following three open-ended questions were asked of drivers upon completion of the trial period;

- Question 1: Were you motivated to recharge at night once a financial incentive was offered?

This was to ascertain whether a financial incentive consciously *was considered* to be a motivating factor for drivers.

- Was it easy or difficult to change your recharging behaviour?

The purpose of this question was to *establish the extent* to which a financial incentive was considered to be a motivating factor for drivers. This question was informed by the literature indicating that behaviours were more likely to be adopted if they were perceived to be easy to implement. This is important to understand as current OLEV policy is based on the unproven assumption that drivers will find it easy to change their behaviour.

- Were there any barriers preventing you from recharging at night?

This question aims to understand whether there were any barriers faced by drivers which prevented them from changing their recharging behaviour, in order to identify any limitations in current policy or changes that need to be made.

Statements were also added to the SwitchEV post-trial questionnaire. The template developed by the SwitchEV consortium allowed users to select from of the five responses, which ranged from ‘strongly disagree’ to ‘strongly agree’. The aim of these statements was to understand SwitchEV driver attitudes toward smart meters and access mechanisms to public recharging infrastructure. The first statement was ‘smart meters would make it easier for me to recharge overnight’. Two statements were then asked, both of which presented drivers with a theoretical scenario in which they had access to a smart meter at home. These were;

- Scenario 1: I would recharge more at home, off-peak if I had a smart meter and the existing NE PiP membership access scheme for non-domestic recharging posts.

- Scenario 2: I would recharge more at home, off-peak if I had a smart meter and pay as you go (PAYG) standard fees for parking and electricity at non-domestic recharging posts.

These questions were asked to all SwitchEV drivers in order to determine whether the current membership access system for non-domestic recharging infrastructure, along with a lack of a smart meter and financial incentive system, is having an impact on driver attitudes to recharging by encouraging greater use of non-domestic recharging infrastructure.

3.5. **Analysis of Focus Group Transcripts and Written Driver Responses**

Focus group transcripts and written responses from drivers were analysed using thematic analysis. A six phase methodology was followed, as described by Braun and Clarke (2006);

- The first phase was a familiarisation process. This involved reading through the entirety of the focus group transcripts until the researcher was familiar with the dataset.

- The second phase was the initial coding of the data. This involved organising individual quotes and comments into meaningful groups, called ‘codes’. The number of groups was dictated by the range of data available. All data extracts were coded.

- The third phase was to apply an inductive approach, discarding all codes that did not fit into the broad category of EV recharging. At this phase, any data that were uncertain were retained.

- Phase four was the initial identification of themes and sub-themes relating to EV recharging. Codes were compared to identify potential themes. All codes were allocated to a particular theme.

- Phase five was the refining of the initial themes and sub – themes, either by combining or splitting, as required. A theme was considered to be a meaningful pattern or series of responses within the data. Sub-themes were differing patterns that related to the same broad theme. All of the original codes were re-read within each theme to scrutinise whether there was a consistency amongst the codes. If there was, then the codes remained as part of the same theme. If not, some of the codes were re-coded to another theme if they was consistent with other codes within that theme, or a new theme was created if there were codes that were not consistent with any of the existing themes.

- The sixth phase was to repeatedly re-read the entire dataset in order to ensure that the themes and sub-themes that have been identified were a correct reflection of the discussion. Further re-coding was undertaken at this phase. The process of re-coding stopped once the refinements were not adding anything new or substantive to the existing code.

When presenting discussion of the thematic analysis results, verbatim records of conversations, with colloquial expressions, were maintained for accuracy of reporting.

3.6. Summary of Methodology Chapter

The aim of this research was to define recharging demand profiles and subsequent carbon content of electricity for EV users in North East England and to quantify the effectiveness of financial incentives and smart meters as demand management tools. To achieve this aim, data were collected from in-vehicle logging equipment as part of the SwitchEV trials, in which four cohorts of users leased EVs for approximately six month trial periods over two years. In addition, focus group discussions and self-completion questionnaires were conducted. All results and transcripts were made available to the author, along with the opportunity to add additional questions pertinent to the research undertaken for this thesis.

Demographic information of the participants, post-trial questionnaire results and the outcomes of the thematic analysis that was undertaken on the focus group transcripts are presented in Chapter 4. This was to identify the characteristics of EV drivers in this study and to understand why specific recharging behaviours were adopted and how future policy can be shaped as a result.

To determine the number of typical recharging profiles, the Eigenvalues associated with the frequency of recharging in each hourly interval of the day were calculated. These were used to inform the number of clusters (recharging profiles) recorded within the dataset. Hierarchical cluster analysis using the squared Euclidian distance with the Ward linkage method was then undertaken to separate drivers into clusters based on their recharging demand. Power generation data from national grid were used to convert these recharging events into equivalent carbon emissions for each user. Analysis was undertaken to understand the impact of user type of the likely recharging demand profile adopted. The recharging profiles identified were then further analysed in order to understand differences in recharging demand based on user type and location. The results of this analysis are presented in chapter 5.

The final stage of this analysis was to assess the effectiveness of financial incentives and smart meters as a demand management tool. Drivers were sent an email at the midpoint of their trial offering them a reimbursement to the value of 50% of the electricity used to recharge their electric vehicles. A subset of comparable users who were not participating in the interventions was used as a control group. To test whether behaviour had changed for a group of drivers, a T-test (normal data) or Wilcoxon Signed Rank test (non-normal data) was undertaken to determine whether the percentage point change in the proportion of recharging taking place off-peak varied between the pre-intervention and post-intervention data for the control group users was significantly different from zero. Additionally, changes were quantified by recharging location in order to understand where changes were taking place. This testing was then repeated for the intervention participants. Analysis to determine whether the carbon content of electricity associated with EV recharging changed significantly between the control and intervention participants was then completed. The intervention analysis is presented in Chapter 6.

4. User Recruitment, Data Collection and Soft Data Analysis

4.1. Introduction

This chapter outlines the total number of different vehicle user types recruited to take part in this study. The demographics and of the sample of users completing the pre-trial questionnaire are compared to the population in the North East of England region, along with a comparison between the attitudes of SwitchEV participants toward the environment compared to the UK general public.

An overview is then presented of the recharging data collected from this study, including the overall profile and the distribution of carbon content of electricity estimated for summer and winter events.

This section also presents the results of the thematic analysis of the focus group data and the responses to the driver questionnaire. These results are referred back to at a later stage of the thesis in order to give context to data analysis of the following chapters.

4.2. Review of SwitchEV Participants

4.2.1. User Types Taking Part in SwitchEV

The number of Nissan and Peugeot users recruited for each of the four SwitchEV cohorts can be seen in Table 4-1. It should be noted that Organisation Pool user vehicles have more than one driver, so the number of individual drivers using these vehicles exceeds the number of vehicles in this table.

User Type	Cohort 1	Cohort 2	Cohort 3	Cohort 4	Total
Private user	5	6	6	6	23
Organisation Individual	17	11	4	11	43
Organisation Pool	17	15	22	20	74
Total	39	32	32	37	140

Table 4-1: Total number of Nissan and Peugeot users by cohort (n = 140)

In total there were 140 Nissan and Peugeot users in this study. Of these, 74 (53% were Organisation Pool users, 43 (31%) were Organisation Individual users and 23 (16%) were Private users. Overall, the majority of vehicles in this study were driven by Organisation Pool users. Private users were under-represented. This was due to the user types requested by the SwitchEV consortium partners, in that the EV manufacturers considered organisation clients, rather than private individuals, as making up the bulk of the early adopter market for electric vehicles and focused on recruiting larger proportions of these user types.

Figure 4-1 shows the recharging infrastructure hosted by each user type.

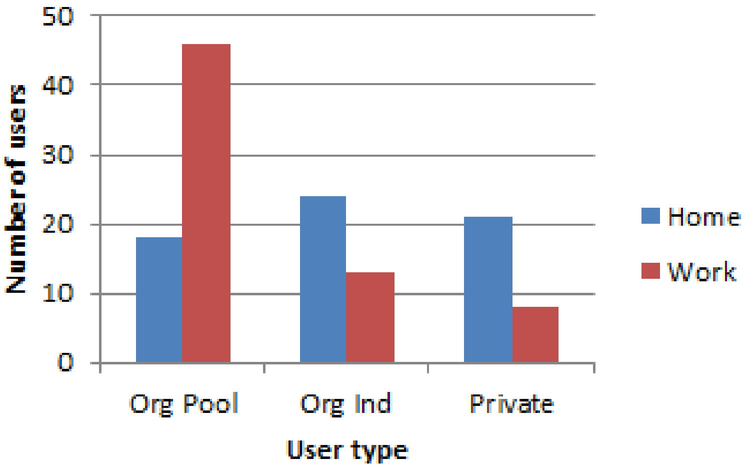

Figure 4-1: Number of recharging infrastructure hosts by user type (n = 140)

18 (24%) Organisation Pool vehicles had a user with access to home recharging infrastructure. 46 (62%) Organisation Pool users hosted a NE PiP post at work. 24 (56%) Organisation Individual users had a post installed at home and 13 (30%) hosted a workplace NE PiP post. 21 Private users (91%) had access to a home recharging unit and eight users (31%) had a workplace post installed.

The lack of recharging access could have influenced the outcome of the interventions. The majority of Organisation Pool users did not have access to a dedicated home recharging point. These home recharging points were the only recharging infrastructure installed within the region which had a control panel that drivers could use to set the start time of the recharging event, rather than the recharging beginning immediately upon the vehicle being plugged-in. For all intervention participants, this lack of timing devices could limit the ability of users to recharge off-peak.

4.1. SwitchEV User Demographics

This section presents the responses to the pre-trial driver questionnaires regarding demographic information. These are compared to regional figures from the UK 2011 Census from the UK Office for National Statistics (ONS) in order to determine to what extent the users taking part in SwitchEV are representative of the population of the North East of England as a whole. For age, statistics were compared to the age ranges of people with full UK driving licenses. This information was not available regionally, so national figures are used for comparison.

Due to the method of recruitment adopted by the SwitchEV consortium, it is not expected that this sample will be representative of the general population. Individuals who have their own company vehicles or make use of pool vehicles as part of their job as likely to not be representative of the population in general. Similarly, the Private users must have sufficient disposable income to be able to pay the vehicle-lease cost and be a homeowner. Therefore, it is expected that professionals and more wealthy individuals are likely to be over-represented.

Figure 4-2 illustrates the age of SwitchEV participants compared to UK national statistics for number of driving license holders (DVLA, 2012).

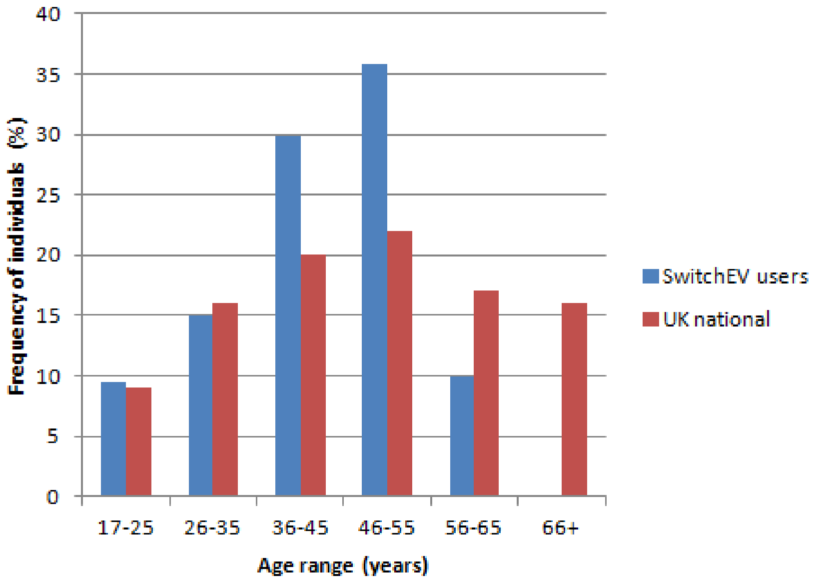

Figure 4-2: SwitchEV users (n=201) by age compared to UK national statistics (DVLA, 2012)

In total, there were 201 responses to this question. It can be seen that, in SwitchEV, users in the 36-45 age range contributed to 30% of drivers and users in the 46 – 55 age range contributed 36%. This compares to 20% and 22% respectively for driving license holders in the UK overall. These age ranges constituted the majority of SwitchEV drivers, and so the SwitchEV driver sample was not representative of UK driving license holders in general. Additionally, there were no drivers aged over 66 participating in SwitchEV. This group is under represented, as 16% of UK driving license holders. Furthermore, insurance requirements limited participation in SwitchEV to drivers over the age of 21. As expected, a Chi-squared test indicates that the SwitchEV user sample was statistically significantly different from the general population at a 99% level of confidence (p<0.00).

Figure 4-3 illustrates the employment status of SwitchEV users compared to those in the region (ONS QS602EW, 2011).

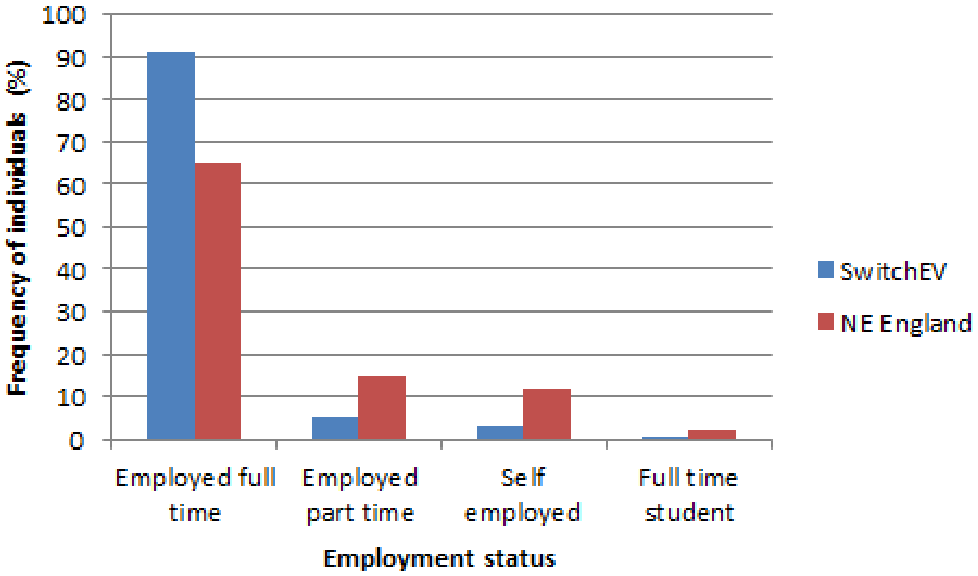

Figure 4-3: SwitchEV users (n = 189) by employment status (ONS QS602EW, 2011)

There were 189 responses to this question. Full time employed individuals were overrepresented in Switch EV, with 91% of drivers in this category compared to 65% of individuals in the region. All other employment types were under-represented in the SwitchEV trial. This was expected because the majority of EVs were leased by organisations. A Chi-squared test indicates that the differences in the employment classifications between SwitchEV participants and the general population in North East England were statistically significant at a 99% level of confidence (p<0.00).

Figure 4-4 shows the distribution of the annual earnings of SwitchEV users.

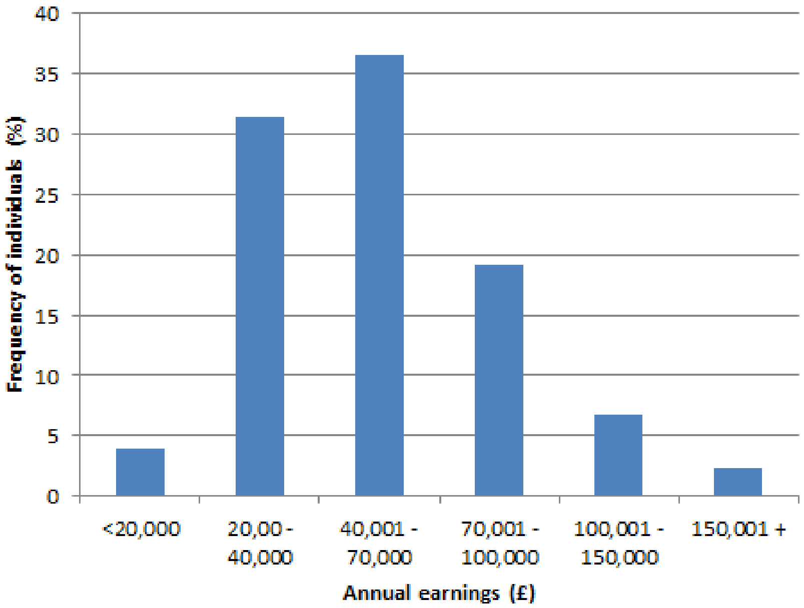

Figure 4-4: SwitchEV users (n = 178) by income bracket

There were 178 responses to this question. The largest income bracket for SwitchEV drivers was £40,001-£70,000, which constituted 37% of SwitchEV drivers. The next largest was £20,000-£40,000, with 31% of users. The median average income regionally in 2012 has been estimated to be £23,665 (ONS, 2012). Therefore lower income drivers were underrepresented and higher earners were overrepresented in the SwitchEV user sample.

The SwitchEV user sample was overrepresented by married, middle aged men in full time, high income jobs compared to the general population of the North East of England. However, the demographics of SwitchEV users were similar to the early adopter traits described in literature; young and middle aged individuals with above average income (Deloitte, 2010; Campbell *et al.*, 2012; Carley *et al.*, 2013). Furthermore, given the high number of organisations leasing EVs for use either as pool vehicles or as vehicles for managers, it would be expected that the sample would be over-represented by individuals in full time occupations with above average income.

In terms of the attitudes of the SwitchEV user sample toward climate change, the response of users to the statement that one of the reasons for their participation was 'to do something to protect the environment' can be seen in Figure 4-5.

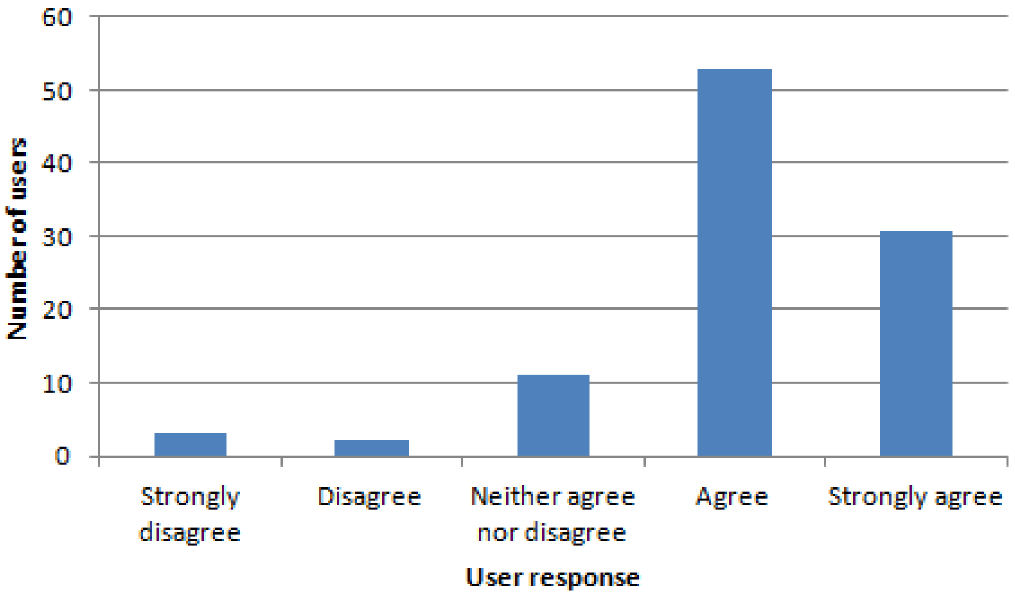

Figure 4-5: User responses to the statement 'to do something for the environment' when asked why they took part in SwitchEV (n = 191)

It can be seen that 84% of users expressed agreement (53% of users agree and 31% of users strongly agree). This compared to 66% of the general public in the UK expressing concern about climate change (Department of Energy and Climate Change, 2013a). Therefore, the sample of SwitchEV users expressed greater environmental concerns than the general population. This result is consistent with the literature stating that attitudes to climate change and the environment can impact on the willingness to adopt new technologies and behaviours (Steg and Vlek, 2009; von Borgstede *et al.*, 2013; Wicker and Becken, 2013).

4.2. Summary of Data Collected

This section presents a summary of the data collected from Nissan and Peugeot vehicles throughout the SwitchEV trial. The data includes the total number of events recorded; the total number of hours and the overall recharging demand profile, for all users and the overall carbon content of electricity distribution, based on all recharging events from all vehicles.
In total there were 16,105 recharging events, constituting 46,536 hours of recharging. The user types and type of recharging location of these events are shown in Figure 4-6. The average duration of these recharging events by user type can be seen in Table 4-2.

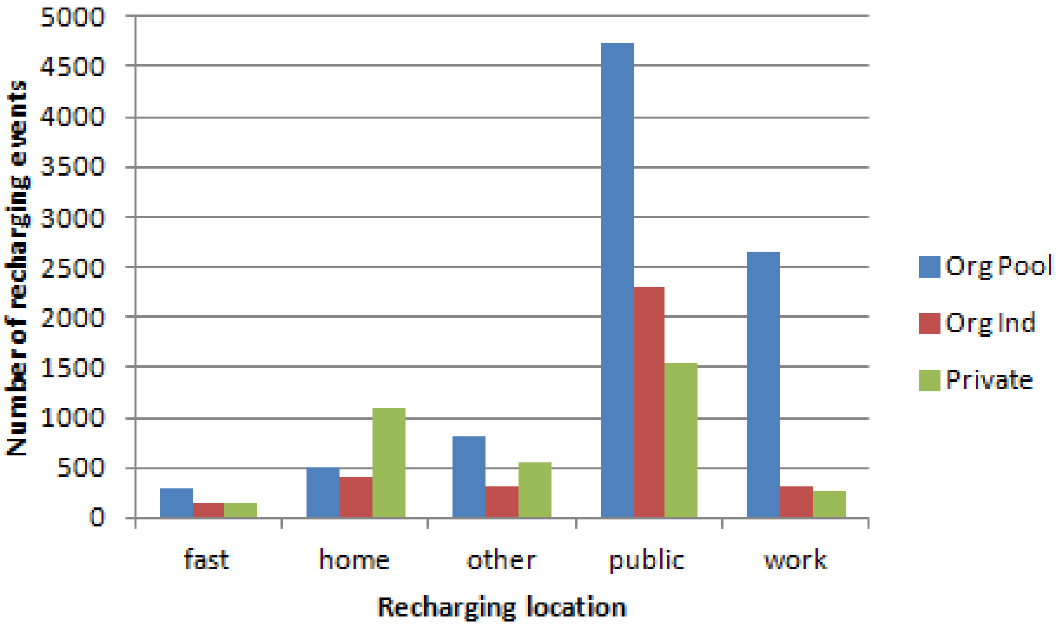

Figure 4-6: Total frequency of EV recharging by time of day for all SwitchEV users in this study (n = 16,105 events)

Recharging Location	Average recharging duration (hours)			
	Org Pool	Org Ind	Private	All users
All	2.80	3.05	2.97	2.89
Fast	0.40	0.54	0.46	0.45
Home	3.01	2.84	2.57	2.74
Other	3.32	3.24	3.31	3.30
Public	2.82	3.20	3.17	2.99
Work	2.81	3.15	4.11	2.96

Table 4-2: Total frequency of EV recharging by time of day for all SwitchEV users in this study (n = 16,105 events)

Organisation Pool users recorded more recharging than any other user type, with a total of 9015 events. This compared to 3482 recharging events for Organisation Individual users and 3608 for Private users.

In terms of locations, for all user types the most frequent recharging location by number of events was public. 4737 (53%) recharging events of Organisation Pool users took place at public locations. 2301 (66%) of Organisation Pool user and 1537 (43%) of Private user recharging also were recorded at public locations. The mean (median) recharging duration was 2.9 hours (2.5 hours).

The overall recharging demand profile for all users is displayed in Figure 4-7.

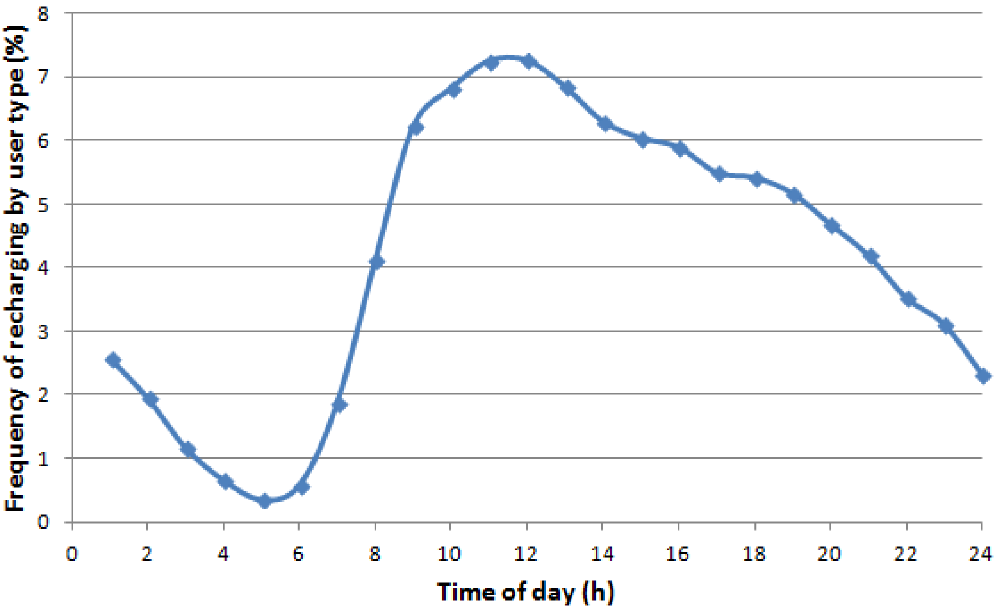

Figure 4-7: Total frequency of EV recharging by time of day for all SwitchEV users in this study (n = 46,536h)

The recharging frequency peaked between 11:00h and 12:00h. This peak constituted 7.2% of EV recharging frequency whilst 57.4% took place between

09:00h and 18:00h and 7.3% between 00:00h and 07:00h, during the off-peak period. The recharging demand profiles by user type can be seen in Figure 4-8.

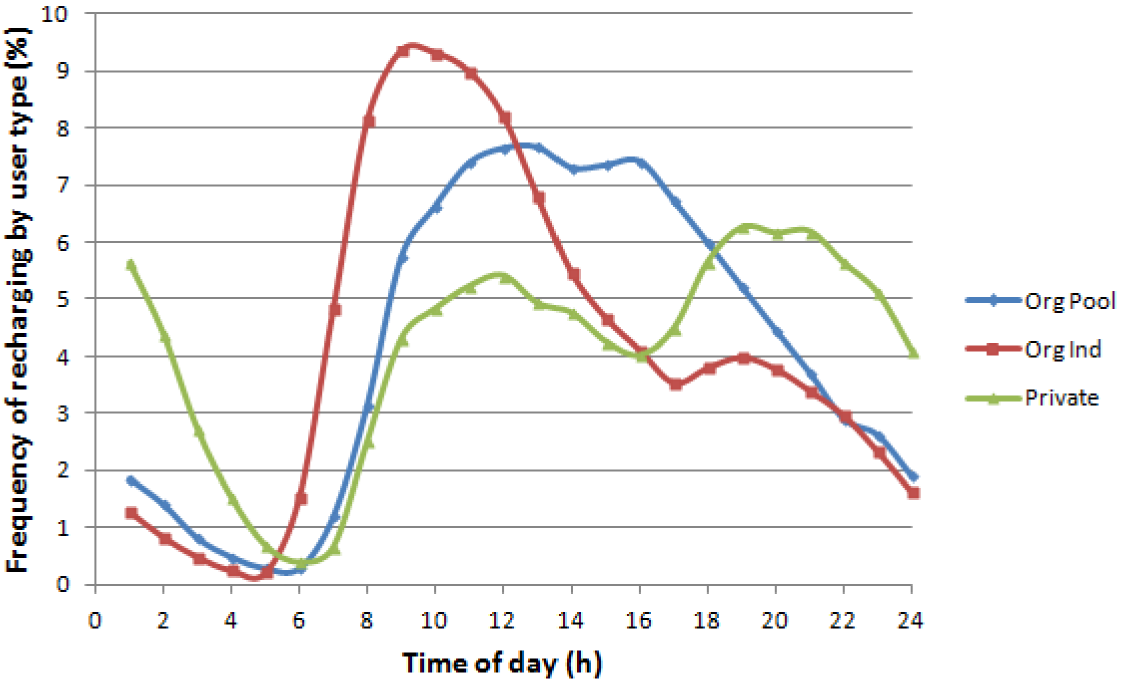

Figure 4-8: Total frequency of EV recharging for all SwitchEV users by user type (n=46,536h)

For Private users, there were two distinct peaks in frequency demand. The first, of 5.3%, occurred between 12:00h and 13:00h. The second, larger peak frequency of 6.2% occurred between 18:00 and 19:00h. It should be noted that all Private users in this study were required to have a home recharging solution. This partly explains why they were the only user type to record a peak in the evening. This is when drivers arrive home at the end of the working day. Pool vehicles had a larger peak frequency between 13:00h and 14:00h, of 7.8%. There was a second, of 7.4%, between 16:00 and 17:00h. For Organisation Individual users, the first peak frequency of recharging occurred between 09:00h and 10:00h. This is when users were arriving either at work or at a public recharging post. The second peak occurred on an evening, with a frequency of 4.0% of recharging taking place between 19:00h and 20:00h.

The recharging demand profiles by location can be seen in Figure 4-9.

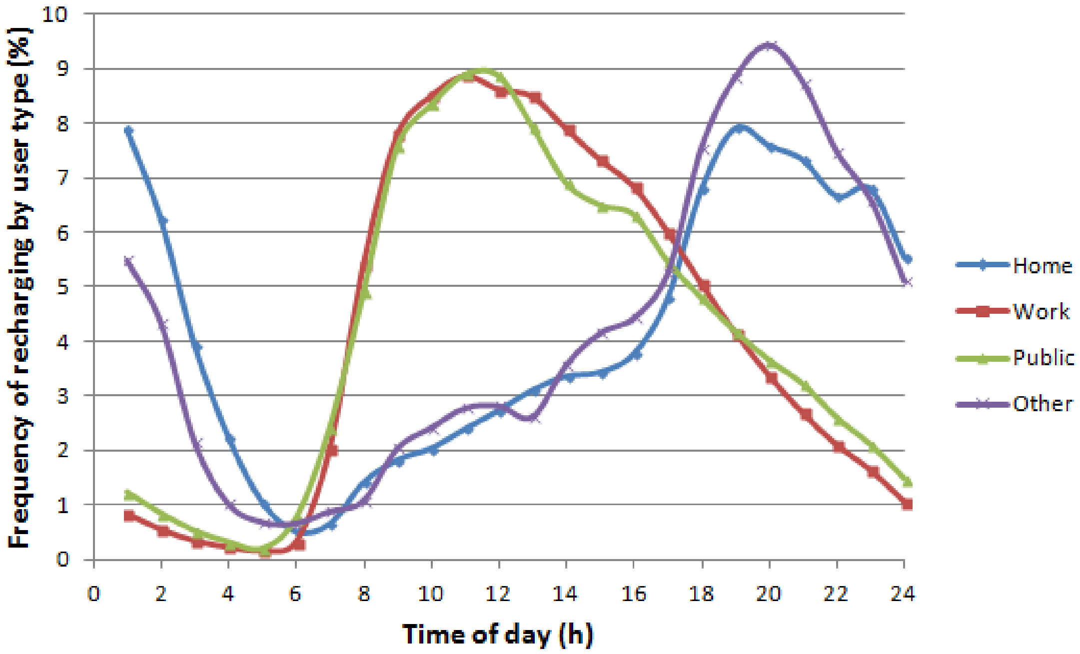

Figure 4-9: Total frequency of EV recharging by location (n=46,536h)

The work and public recharging demand profiles followed a similar demand frequency throughout the day. At work, 8.8% of recharging frequency occurred between 11:00h and 12:00h. At public locations 8.9% took place between 12:00h and 13:00h.Home and Other locations were also used in a similar way. Home had a peak frequency of 7.8% between 18:00h and 19:00h. On the other hand, Other had a recharging frequency peak between 19:00h and 20:00h, of 9.4%. This suggests that other recharging events were taking place at domestic locations, using standard three pin plugs, rather than recharging posts. This is likely if a recharging event was needed but a dedicated home recharging device had not been installed.

This recharging behaviour did not follow the off-peak demand strategy outlined by the Office for Low Emission Vehicles (2011). The results of this study are in contrast to the CABLED trial, where a recharging demand peaked between midnight and 01:00h (Bruce *et al.*, 2012). Additionally, this result is in contrast to the UK MINI E trial, where recharging also peaked between midnight and 01:00h. (BMW Group, 2011).

Figure 4-10 illustrates the distribution of carbon content of electricity per recharging event.

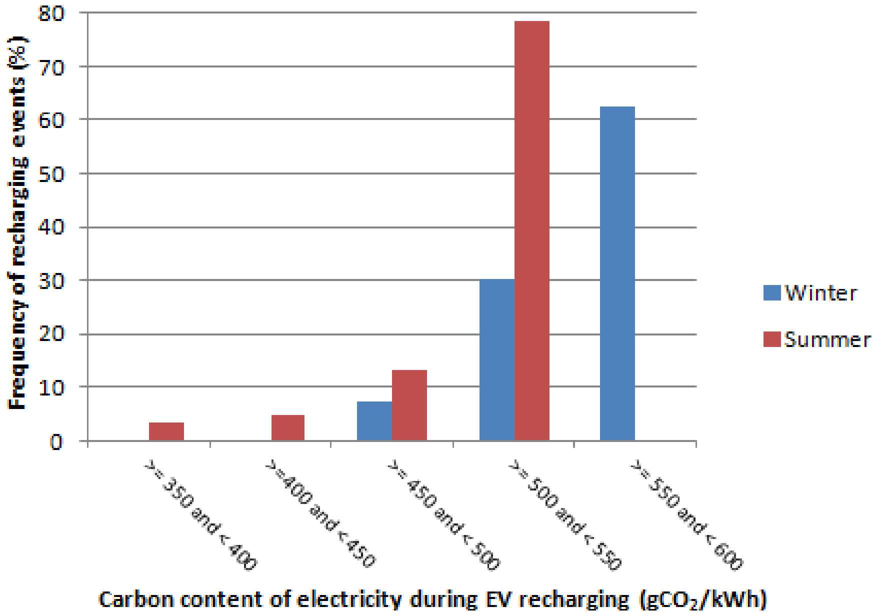

Figure 4-10: *Carbon content of electricity during EV recharging using typical winter and summer recharging profiles based on all recharging events by all vehicles*

The average (median) carbon content of EV recharging was 546 (553) gCO_2/kWh in winter. The maximum carbon content of electricity in any given half hourly interval was 562gCO_2/kWh and the minimum was 472gCO_2/kWh. In summer the average (median) was 508 (522) gCO_2/kWh. The maximum half hourly value of the carbon content of electricity was 534gCO_2/kWh and the minimum was 385gCO_2/kWh. The carbon content of electricity in winter is higher, due to an increase in the proportion of electricity generated from coal power stations. It is thought that this explains why the carbon content of electricity during EV recharging being higher in winter than in summer.

4.3. Thematic Analysis Results

4.3.1. Key Themes Identified

This section presents the results of the thematic analysis of the focus group discussion. Three core themes relating to the recharging of EVs were identified within the focus group discussion. Figure 4-11 illustrates the themes and sub themes identified through the coding of the focus group discussion.

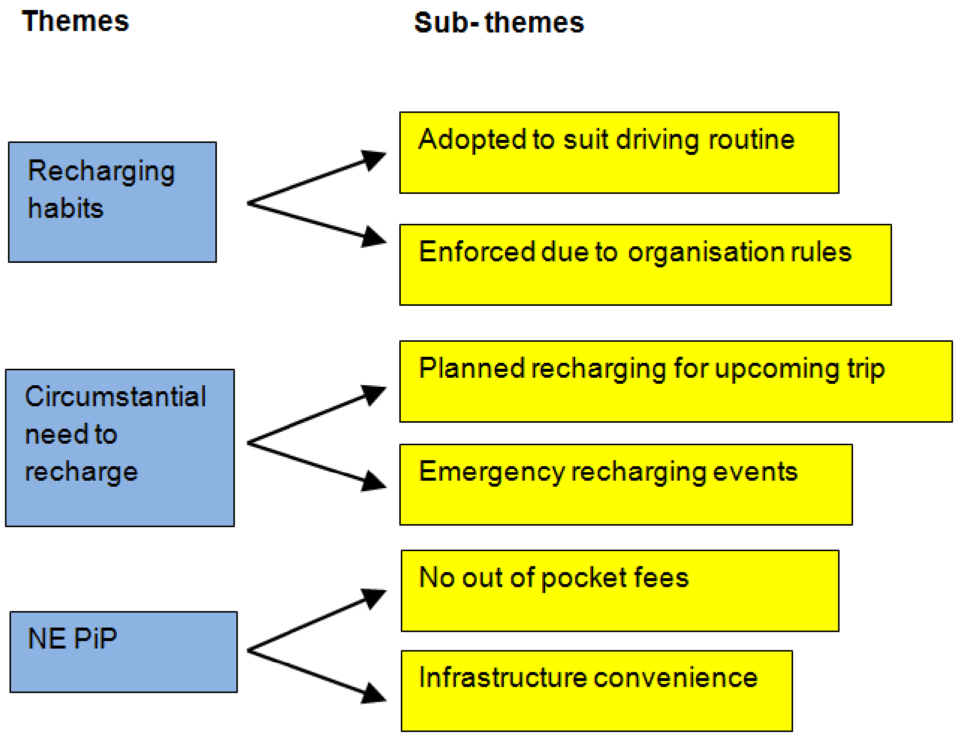

Figure 4-11: Themes and sub-themes identified through thematic analysis

4.3.2. Review of Theme One – Recharging Habits

The first theme was the habitual recharging of electric vehicles, and there were two sub themes within this. One sub-theme relates to habitual recharging routines. The second sub-theme related to organisation-imposed rules on users regarding EV recharging. These rules were in place when Organisation Pool vehicles were required for use by other individuals later in the day, and so the organisation had a policy that all vehicles must be recharged upon returning to 'base'.

Examples of driver comments regarding habitual recharging that has been influenced by the users typical trip/commute patterns can be seen below;

"We mostly 'home' quite a lot, we mostly take the EV out and bring it back here [company HQ] to charge it."

"The standard procedure is to take it out during the day, it's then brought back and it getting charged to a full top-up overnight. So that's our current procedure, but if you could put additional top-up charge in the EV whilst you were out, at a location with a CP, then you would take advantage of that as well."

“We tend to top up every night. Sometimes just for a couple of hours if it’s only been used say for 20 miles either 2, 3 hours on a normal charger will bring it right back up again so that one normally is fully charged on a morning.”

A quote demonstrating that some organisations require the EV to be recharged at the organisation ‘base’ is;

“*If it’s not being driven, it’s charging.”*

The identification of these themes reveals that driver’s recharging habits can be based on either an adopted habit that the driver has made due to their own requirements, or a regime that has been deemed necessary due to the EV having multiple users in one day.

Empirical data quantifying the difference in time between the end of a trip and the start of a recharging event can be seen in Table 4-3 .

	Time between trip end and recharging start			
Location	**0-5 mins (%)**	**5-30 mins (%)**	**30-60 mins (%)**	**>60 mins (%)**
CYC	82	6	2	9
Home	78	7	2	13
Other	82	6	1	11
Work	86	6	1	6

Table 4-3: Percentage of durations between the end of a trip and the start of a recharging event by location (each location total = 100%).

It can be seen that, typically, vehicles were recharged within 5 minutes of the previous trip. Work was the location at which the highest percentage of recharging events took place within 5 minutes (86%) and the lowest that were more than an hour after the trip was complete. This validates the statements from drivers that organisation policy at work recharging infrastructure can influence demand.

4.3.3. Review of Theme Two – Circumstantial Need to Recharge

The second theme was the circumstantial need, or perceived need, to recharge the EV. The two sub themes were the need to recharge an EV before a known upcoming trip in order to ensure the journey can be completed and the need to recharge in an emergency, when the battery was almost flat and the remainder of the trip could not be completed. An example quote describing the need to recharge the EV before an upcoming trip is;

"The other night I had about 20 miles and my commute's 10 miles to work and I knew I had 20 miles and it's touch and go whether I would have made it and I pulled up at the charging point and I couldn't get into the charging point so, you know, I had to drive out to find a charging point because I was that worried because I just did not think my 20 miles would get me to work and then it is that and what hap-...what does happen, what does happen if you're on your way to work and you just run out of electricity what happens. I have no idea what I would do."

Some example quotes describing the recharging of an EV in an emergency include;

"I did take the car from Newcastle to Berwick to use the FCP (fast charging post) there and it was a real struggle getting back, we ran out of battery about 10 miles north of Newcastle and had to drive very slowly in order to get back, my heart was racing and I was really uncomfortable, I had all these scenarios running through my head about having to find out who I had to phone to come and get the car charged… the battery meter had been on zero for a long time and it was flashing, and we eventually crawled through to Gosforth and plugged it in at the first charge point I could find and the panic was averted."

" I'd ran dangerously low and I was up at the Beamish Hall Hotel and I had to ask someone at reception if I could plug in somewhere and they allowed me to park right up to a bedroom window and they led the cable through the window into the bedroom and plugged it in there."

This illustrates that some recharging events were planned due to a perceived or actual necessity to complete an upcoming journey. This is different from the habitual recharging discussed as part of the previous theme, which is completed as required, rather than being repeated as a component of a recharging routine. This indicates that drivers are aware of the limitations of their vehicle, and that the public recharging infrastructure allows them to complete trips that they would not otherwise be able to complete.

The second sub-theme within the need to recharge theme was the emergency recharge, which occurred mid-trip, where a driver was not able to complete the remainder of the trip due to the range of the EV limited by the charge remaining in the battery. Providing support for this type of recharging is a challenge and more difficult to manage, as the driver had not anticipated a situation occurring and requires an imminent recharge.

4.3.4. Review of Theme Three – Influence of North East NE PiP

The third recharging theme identified was recharging utilising the NE PiP membership scheme. There were two sub-themes in this category. One sub-theme was the recharging of EVs due to the unlimited access to parking and recharging of EVs through NE PiP. The other related to perceived levels of availability of recharging infrastructure at different geographical locations on the NE PiP recharging infrastructure.

Example quotes suggesting that the absence of out of pocket cost encouraged recharging of EVs at public recharging infrastructure are;

“One of the benefits, we didn’t mention before, of having an EV not only reduce tax and other costs, is the free parking in Newcastle. You would take the opportunity, even if you didn’t need a charge, to find an EV bay because you knew it was free and hopefully be available.”

“I’m going to town partly because I’m taking part in the trial and the idea anyway of the trial is to use our cars as much as we can but I think, actually, as you say it’s free parking in Newcastle you drive in to Newcastle rather than get the Metro wouldn’t you.”

This suggests that there were some drivers whose recharging behaviour was influenced by the nature of the NE PiP membership scheme in which they were taking part.

Some quotes from drivers who do not feel the NE PiP membership setup influenced their decision to recharge at public recharging points are;

“I think if I was fully committed to having one I would be willing to pay because obviously if I was fully committed and you’re willing to do away with the second car and therefore use it for whatever business or pleasure journeys there will be times when you need – you’re away from home – you do need to charge it so yes I think if you buy into the concept I think you should be willing to accept that there will be times that you need to pay for charge. It can still work out far cheaper than having to fill a petrol or diesel car up every other week.”

“The free parking is a fantastic side benefit at the moment but it didn’t change our habits. It didn’t encourage us and having the car didn’t encourage us to use the car any more or any less but obviously the free parking is a hidden benefit at the moment which I don’t think people are taking into consideration.”

The second sub-theme involved discussion of the convenience of the Ne PiP recharging network in the region. There were some drivers who felt that the network was convenient during their trial period and others who did not. Some drivers felt that some locations were convenient but not others.

Example quotes from drivers who feel that the public network of recharging posts was convenient for their usage in are;

“I now find I’m doing journeys that I would otherwise do by public transport today I drove here whereas normally I would have got the metro but because there’s always I usually find an electric parking space and usually I can charge up while I’m there then I tend to drive a little bit more than I would otherwise as it were so that’s maybe a negative.”

“*You get a better parking spot. So you park closer to where you want to be.”*

“For me if I go to Newcastle...there are lots of them, they’re in good locations and I know I can get one”

From the above quotes it is clear that some drivers found the recharging infrastructure sufficiently convenient that it encouraged them to drive the EV into the centre of Newcastle, when otherwise they may have used alternative modes of transport. The free parking element was seen by some as the main motivation for some users to utilise city centre recharging posts, whereas others were encouraged primarily by the convenience of the city centre parking spaces relative to their final destination. Given that most SwitchEV drivers are professional people with above average earnings this is likely to refer to parking on a daily basis when travelling to work.

However, most drivers had suggestions regarding locations where they feel that there should be more recharging posts, or that the current network was not sufficient;

“Once we get more CP infrastructure out there then I think we’d be more comfortable that we could start to go further.”

“The journeys I make though, are often to places where there isn’t an opportunity to charge.”

“I think the Northumberland coast would benefit from CPs, Seahouses has thousands of visitors over the summer and there is a really high visibility rate there”

The centre of Newcastle was considered to have both adequate and convenient recharging network that drivers could use. However, the rural areas of the North East of England were generally considered to be lacking in recharging infrastructure. Some drivers stated that this limited the use of EVs when travelling to some locations.

This provides a further indication that EV drivers are willing to use their EV more, and feel more comfortable driving an EV instead of using public transport or their petrol/diesel equivalent vehicles, when recharging infrastructure is provided in some instances due to price and parking incentive of NE PiP. As the North East of England has a denser network of recharging posts available when compared to other studies of EV recharging behaviour, this can be used to add context to the recharging profiles found in this study if they are found to be different from other studies.

4.4. Post-Trial Online Questionnaire Responses

This section presents the results and analysis to a sub-set of questions from the post-trial questionnaire that drivers completed online. The user responses to the statement ‘I need to use work/public recharging posts in order to complete my daily trips’ is displayed in Figure 4-12.

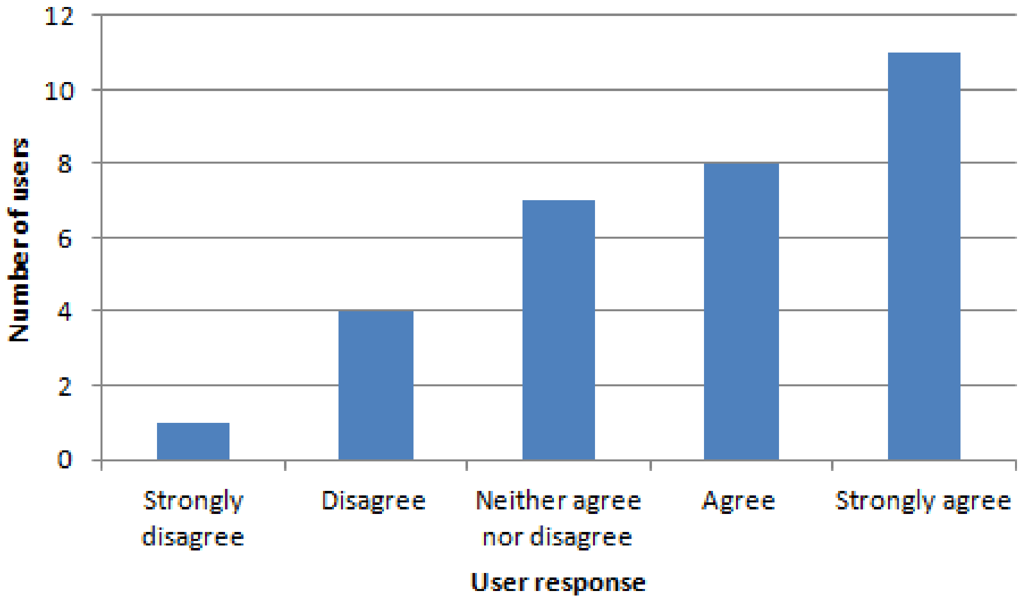

Figure 4-12: Users’ responses to the post-trial statement ‘I need to use work/public recharging posts in order to complete my daily trips’ (n = 31)

It can be seen that the majority (61%) of drivers were in agreement with this statement. Over half of drivers stated that the non-domestic recharging infrastructure necessary for them to complete their daily trips. However, this was proven to actually be unnecessary, because only 7% of the daily trips required public recharging when drivers had access to alternatives for the first two cohorts of SwitchEV users (Higgins *et al.*, 2012). Therefore, there is a difference between the actual and perceived recharging requirements of drivers. Given that 47 out of 51 of the drivers discussing habits in the focus groups said that their recharging was habitual and followed a routine, it could be speculated that a drivers recharging habits were based on how easy it was for them to access the recharging infrastructure as part of their daily routine. If a driver has access to recharging infrastructure at the end points of their journeys, it is likely to be utilised, regardless of whether it is needed to complete an upcoming trip or not. The issue of the perceived ‘free’ parking and electricity at the non-domestic recharging infrastructure could also be a contributory factor.

Therefore, it is important to understand the impact of financial incentives in the North East of England region because as other recharging infrastructure networks develop and the number of EVs on the road increases, the need to balance recharging infrastructure provision with the management of demand during on-peak hours to reduce the risk of overload of power grids increases. The responses to the statement ‘I recharge my EV at every opportunity’ are presented in Figure 4-13.

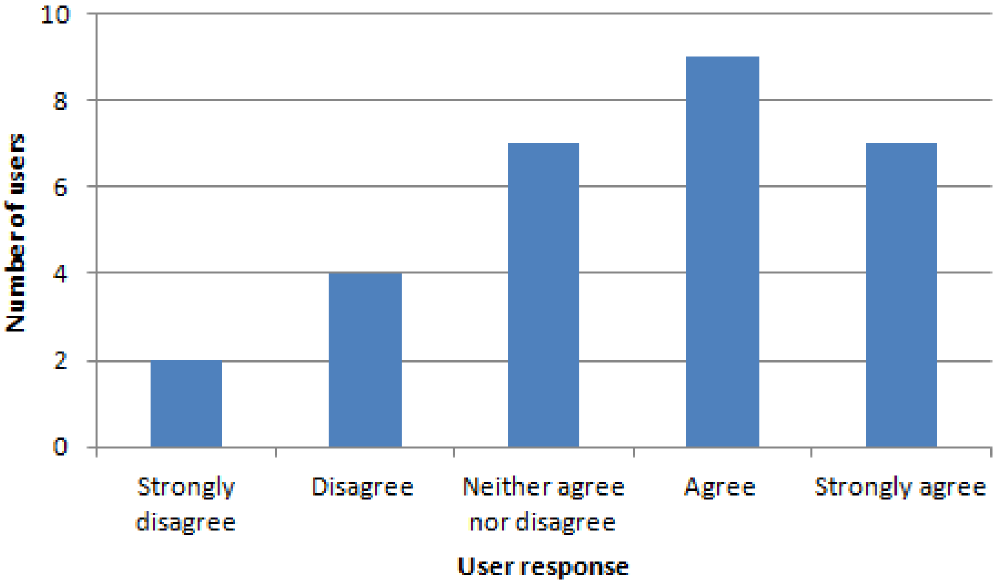

Figure 4-13: Users’ responses to the post-trial statement ‘I recharge my EV at every opportunity’ (n = 29)

Half of drivers recharged at every opportunity (responded with ‘agree’ or ‘strongly agree’). A driver with access to recharging infrastructure at the end points of their journeys would therefore be willing to use it. The convenience of recharging posts and the lack of out of pocket cost, as discussed in focus groups, explains this behaviour. This behaviour might not be repeated in other regions if there are different recharging infrastructure provisions or access mechanisms. This will be revisited in the discussion chapter of this thesis.

4.5. Summary of Key Findings

- **An unbalanced sample of 23 Private users, 43 Organisation Individual users and 74 Organisation Pool users participated in SwitchEV.**

The Organisation Pool users were over-represented in this sample and the Private users were under-represented. The first implication of this is to consider, when allocating user types into recharging profiles following the cluster analysis, it is important to determine the percentage of each user type and not the absolute number of users.

The second implication is that the size of the potential group of intervention participants who were Private users was limited. Therefore, statistical tests need to be carried out with caution.

- **Most recharging took place during the on-peak hours at public recharging locations.**

Of the 16, 105 recharging events, constituting 46,536 hours, recorded overall, 7.3% was recorded during the off-peak hours and 55% took place at public locations.

As a result of this recharging behaviour, the average carbon content of electricity used to recharge EVs during this trial was close to the maximum values. The average carbon content of EV recharging was 546gCO_2/kWh in winter. This was 16gCO_2/kWh below the maximum value and 74gCO_2/kWh above the minimum value. In summer the average was 508gCO_2/kWh. This was 26gCO_2/kWh below the maximum value of 534gCO_2/kWh and 123gCO_2/kWh above minimum value of 385gCO_2/kWh.

- **The SwitchEV users were not representative of the general public.**

The users taking part in this study were not representative of the general public in terms of their demographics. The group of SwitchEV users were over-represented by professional, married men in the 36 to 55 age range, with an income above the region median. It was also inferred that SwitchEV users were more environmentally concerned that the UK general population. This could have influenced the results of this study. If members of the wider population adopt EVs, they might not be as willing to recharge their EVs off-peak due to environmental concern. Conversely, members of the wider population might be more interested in financial incentives being offered to manage recharging demand due to their generally lower incomes relative to SwitchEV participants.

- **Drivers adopted recharging habits based on their daily routine**

Focus group discussion indicated that drivers planned their recharging habits around their daily routine. Therefore, some recharging demand may be difficult to manage due to operational reasons. Furthermore, organisation rules limited many of the Organisation Pool users to recharging immediately upon returning to base.

- **Non-domestic recharging infrastructure within the NE PiP network was perceived to be convenient and ‘free’**

The NE PiP network was perceived to provide convenient and ‘free’ parking spaces for EVs at recharging bays. Drivers considered Newcastle city centre to have a well-developed and accessible public recharging infrastructure. Furthermore, these recharging posts were considered to be located at convenient locations within the city. This created an incentive for drivers to recharge at non domestic locations during the on-peak hours. Some drivers were recharging to gain access to a free parking space, rather than due to a need to recharge their EV.

- **Organisation Pool users reported company policy dictating that EVs must be recharged upon returning to base**

The focus groups identified that organisations have a policy of EVs being recharged upon returning to base. This is an important fact for policymakers because this rule imposes a restriction on the recharging of EVs. This practical limitation was predicted in literature, which stated that usage patterns could impact recharging profiles.

This rule was in place to because of concerns regarding the ability of an EV to complete subsequent trips once the first trip of the day had been completed. In future, there is a need for greater fleet management tools in order to give fleet managers confidence in the EV being able to complete trips whilst managing the recharging demands to reduce loads on power grids and to ensure recharging takes place when the carbon content of electricity is low.

5. Derivation and Analysis of Recharging Profiles

5.1. **Introduction**

This chapter identifies the overall recharging profiles that were observed within the SwitchEV dataset during the pre-intervention period and the subsequent research and analysis undertaken to gain a fundamental understanding of what governs these profiles.

The aim of the analysis was to understand the differences between the profiles in terms of user type and use of recharging infrastructure by location. This was to determine when and where demand peaks are to be expected, and inform future policy regarding recharging demand management.

Initially, the period of time which defined the pre-intervention period was identified. A cluster analysis was then used to identify statistically similar groups of drivers in terms of their recharging demand profiles. The number of clusters (recharging profiles) was identified, and compared to clustering solutions for one more and one less cluster than the solution suggested. This addressed the sensitivity of the profiles to the number of clusters.

The recharging profile allocation by user type was then analysed, to determine the distribution of user types and whether there was a significant difference between different user types.

For each of the recharging profiles, the shape and proportion by location for each user type was compared to determine where the similarities and differences occurred. Finally, an analysis comparing how the recharging demands at each location differ depending upon the user cluster was carried out.

5.2. Defining the Pre-Intervention Period for Control Group Users

In total 21 users agreed to take part in the intervention process. A comprehensive review of the intervention participants can be found in Chapter 6 of this thesis.

A Shapiro-Wilk test was conducted on the distribution of the number of days that an intervention participant had completed of their trial period when they agreed to take part in the intervention (n = 21).This confirmed a normal distribution (p = 0.24) at a 95% level of statistical confidence. Therefore the mean value was the most appropriate centrality measure for this distribution. The mean value was 77.8 days (±15.1 days).

Therefore, all recharging events for drivers not participating in interventions that took place before 78 days or more were classified as the equivalent pre-intervention for comparison purposes and all recharging that took place 78 days into the trial or beyond were classified as the equivalent period for post-intervention recharging.

5.3. Identification of Clusters within the Pre-Intervention Recharging Data

5.3.1. Number of Clusters

This section presents the results of the Eigenvalue analysis used to establish the number of clusters with significant differences in recharging profiles in the region. The Scree plot for the user recharging data can be observed in Figure 5-1.

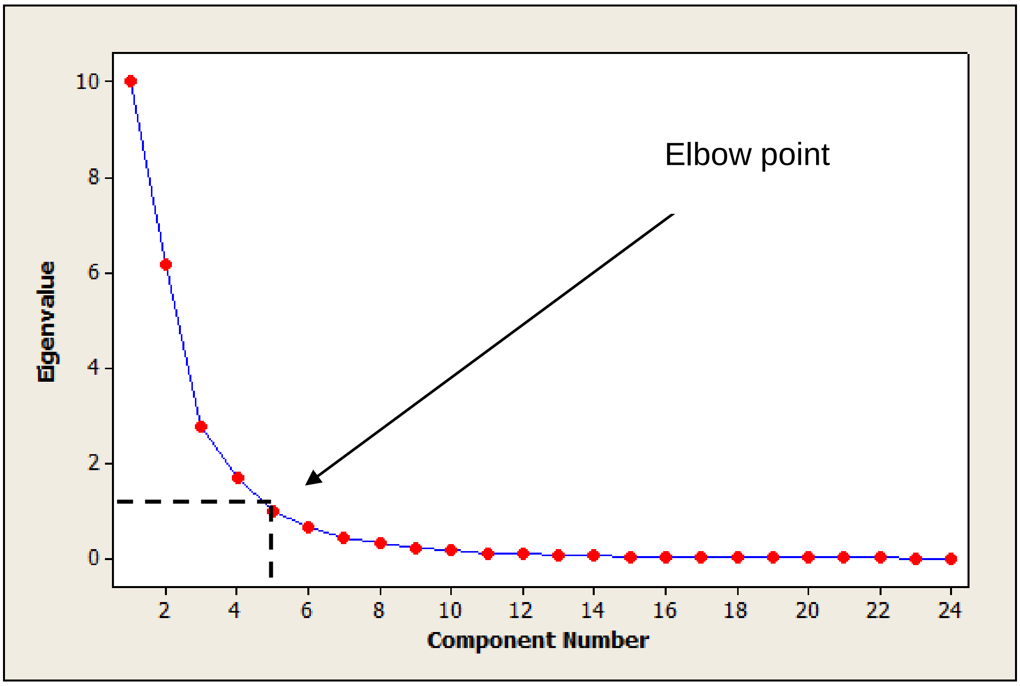

Figure 5-1: Scree plot for clustering of driver recharging profiles

The Eigenvalues were 1.9 for a four cluster solution, 1.1 for a five cluster solution and 0.8 for a six cluster solution. A five cluster solution was therefore selected. This is further verified by the position of the elbow point. Therefore, solutions were tested for four clusters and six clusters.

5.3.2. Overall Recharging Demand Profiles for Four, Five and Six Cluster Solutions

The recharging profiles for each cluster using the four cluster solution are illustrated in Figure 5-2.

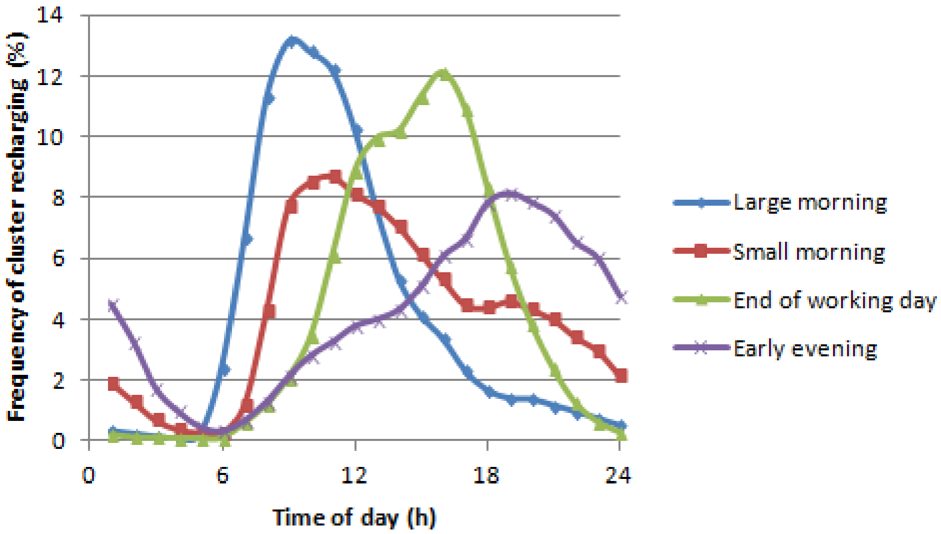

Figure 5-2: Overall recharging demand profiles for a four cluster solution

There were four distinct recharging profiles using a four cluster solution. These were to indicate the relative size and time occurrence of the peak frequency and in this case were named ‘early evening’, large morning’, ‘small morning’ and ‘end of working day’, based on time times of day that peaks were observed. The recharging profiles for a five cluster solution are presented in Figure 5-3.

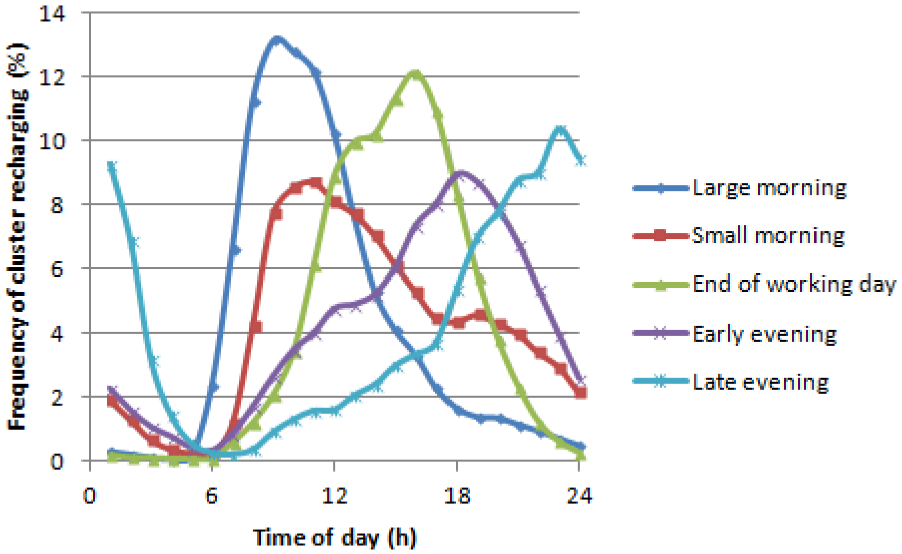

Figure 5-3: Overall recharging demand profiles for a five cluster solution

In cluster five, the additional recharging profile was called ‘late evening’. This was cluster was formed by the splitting of all users in the early evening profile from the four cluster solution. Therefore, both evening profiles showed a degree of similarity relative to the other profiles. Figure 5-4 illustrates the recharging profiles for the six cluster solution.

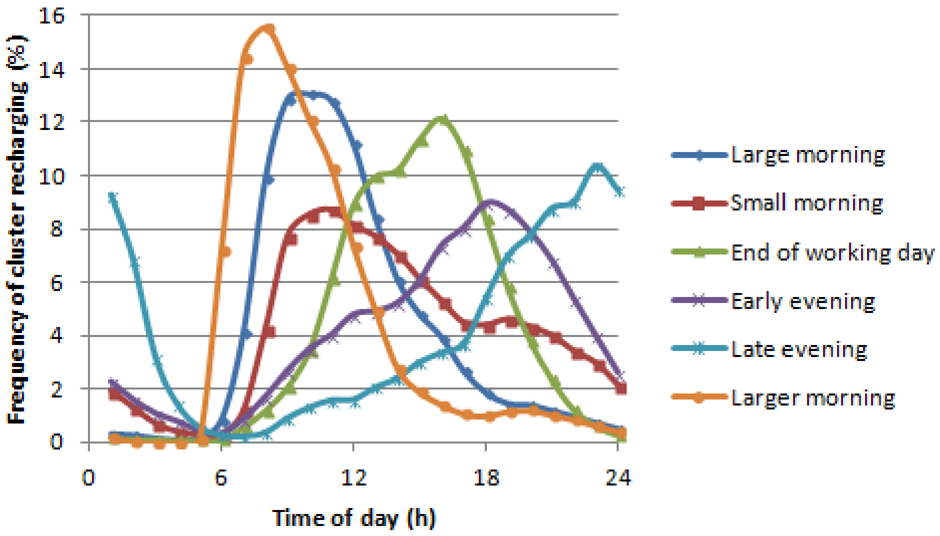

Figure 5-4: *Overall recharging demand profiles for a six cluster solution*

The sixth additional recharging profile was referred to as ‘larger morning’. This was generated by the splitting of the large morning profile into two clusters. The allocation of users into each cluster for the four, five and six cluster solutions are illustrated in Figure 5-5 and the data are presented in Table 5-1.

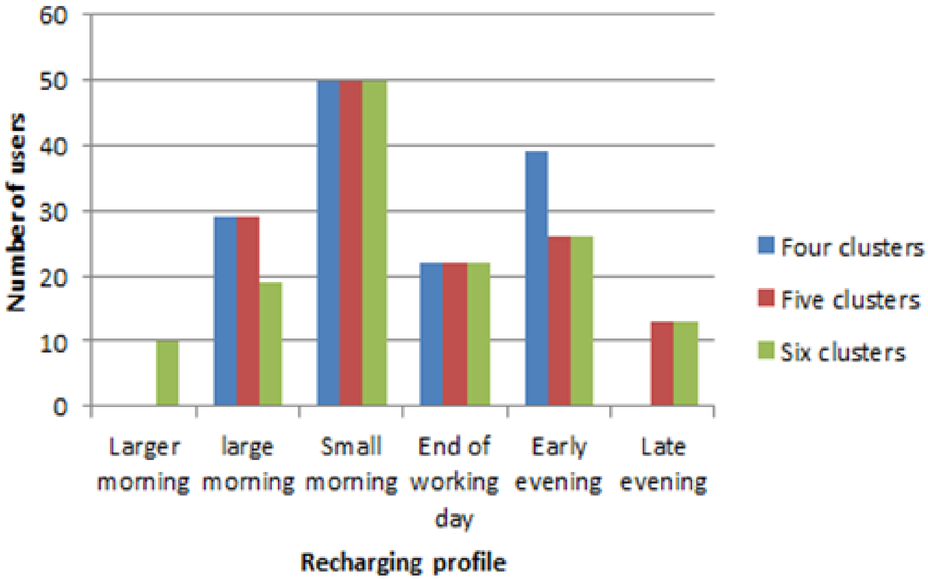

Figure 5-5: Allocation to recharging profiles by clustering solution (n = 140)

Recharging profile	Number of clusters		
	4	5	6
Small Morning	50 (36%)	50 (36%)	50 (36%)
Large Morning	29 (21%)	29 (21%)	19 (14%)
Larger Morning	0 (0%)	0 (0%)	10 (7%)
End of working day	22 (16%)	22 (16%)	22 (16%)
Early evening	39 (28%)	26 (19%)	26 (19%)
Late evening	0 (0%)	13 (9%)	13 (9%)

Table 5-1: Number (percentage) of users allocated to each recharging profile for four, five and six cluster solutions

In essence, the small morning and end of working day groups remain the same whether four, five or six clusters are selected. A four cluster solution fails to differentiate between the early evening and late evening profile, whereas a six cluster solution identifies an additional morning recharging profile. On balance, the five cluster solution is the most suitable choice because the late evening profile that is not identified in the four cluster solution represents delayed recharging into the off-peak hours, a key area of investigation of this research. The six cluster solution, with the separation of two morning peaks, does not add any additional research interest. For these reasons, along with the Eigenvalue greater than one rule and the elbow point of the Scree, plot, the five cluster solution was selected for further research.

5.4. Analysis of the Five Cluster Recharging Profiles Solution

Users following the large morning peak recharging profile had a demand peak of 13% of the total hourly recharging frequency recorded between 08:00h and 09:00h. 10% of recharging took place during the off-peak hours.

The small morning recharging profile had a smaller peak (9%) than the large morning recharging profile (13%). This peak occurred between 10:00h and 11:00h. Off-peak recharging accounted for 6% and 10% of the total frequency respectively for small and large morning users.

Users following the end of working day demanded recharging earlier, between 15:00h and 16:00h, compared to the early evening cluster between 17:00h and 18:00h respectively with 12% and 10% occurring at these peaks. Recharging during the off-peak hours for the end of working day users was higher at 7% peak frequency compared to 1% for early evening.

The recharging demand of users following the late evening recharging profile was quite different with a frequency of 10% between 22:00h and 23:00h with 22% taking place off-peak. As seen in Figure 5, the most frequently occurring recharging profile was the small morning peak profile. 50 users (36% of users) followed this profile. The least frequent recharging profile was late evening, with 13 users (9%).

5.4.1. Recharging Profile Allocation by User Type

Figure 5-6 shows the total number and proportion of each user type allocated into each cluster.

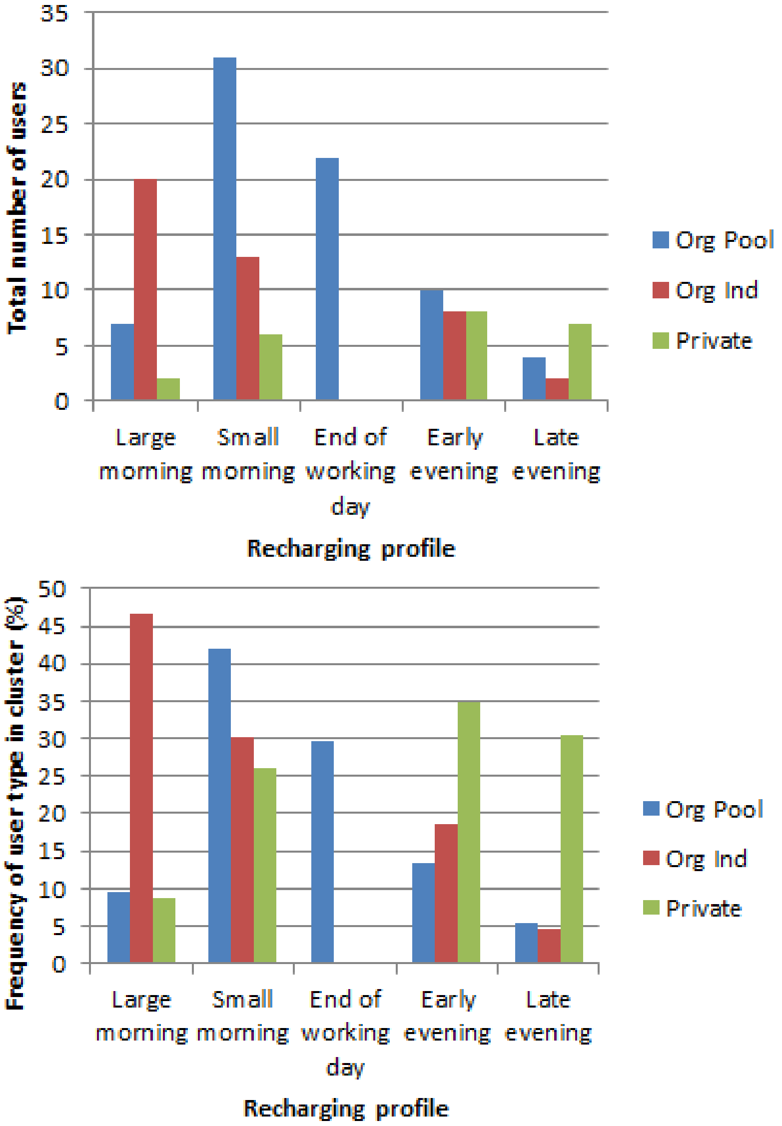

Figure 5-6: Cluster allocation by user type for number of users (above) and percentage of users (below).

Private users recharged predominantly in the evening, with 30% and 34% following the late and early evening recharging profiles, respectively. The remainder were allocated into the small (26%) and large (9%) morning recharging profiles with no Private users were allocated to end of working day.

The Organisation Individual users were allocated in a different manner to the Private users, given slightly higher small morning (30%) and large morning

(46%) profiles, and lower early evening (19%). 4% of Organisation Individuals were allocated to the late evening recharging profile.

Organisation Pool users revealed different recharging patterns, with the two most frequent recharging profiles for Organisation Pool users being the small morning (42% of all pool users) and the end of working day (30%) profiles. Interestingly, the end of working day profile was exclusively Organisation Pool vehicles. This was the only cluster of users to contain drivers exclusively of one user type. The early evening profile accounted for 14% of Organisation Pool users, and the late evening 5%.

Chi-squared tests were conducted to test the hypothesis that the user types were equally distributed into each of the clusters. Both the Organisation Pool and Organisation Individual users were not equally distributed, with χ^2 (4) = 34.8, p = 0.00 and χ^2 (4) = 31.1, p = 0.00 respectively. For Private users, the sample size was not large enough to give an expected cell count of five for all cells. Therefore, the end of working day and early evening cells were merged. A Chi-squared test indicates that Private users were not equally distributed, with χ^2 (3) = 3.96, p = 0.27. Therefore, each of the clusters were characterised by different types of user.

Chi-squared tests were used to compare whether there were significant differences between each of the user types in terms of cluster allocation. When comparing Organisation Pool and Organisation Individual users, the expected cell counts were combined for late evening as these were below five (3.8 and 2.2 respectively). By merging the early and late evening cells, all cell counts were above five. The allocation of user types into recharging profiles between these user types was found to be significantly different, with χ^2 (3) = 30.2, p = 0.00.

When comparing the Organisation Pool and Private users, the expected cell counts for Private users were 2.3, 4.2 and 2.6 respectively for the large morning, early evening and late evening profile. The large was combined with the small morning user frequency counts and the early evening with the late evening to ensure that all expected cell counts were above five. The difference in cluster allocation between these user types was statistically significantly different, with χ^2 (2) = 20.4, p = 0.00.

For private and Organisation Individual users, the early evening was combined with and late evening recharging profile cell counts to keep expected cell counts above five for the end of working day recharging profile. The cluster allocation of user type was significantly different, with χ^2 (2) = 13.5, p = 0.00.

This indicates that user type has a significant impact on the recharging profile adopted. Organisation Individual users were most likely to recharge on a morning, Organisation Pool users at the end of the working day and Private users on an evening.

5.4.2. Overall Duration of Recharging by Location

Figure 5-7 illustrates the relative usage of recharging infrastructure by location for all recharging events that constituted the profiles used to define the clusters.

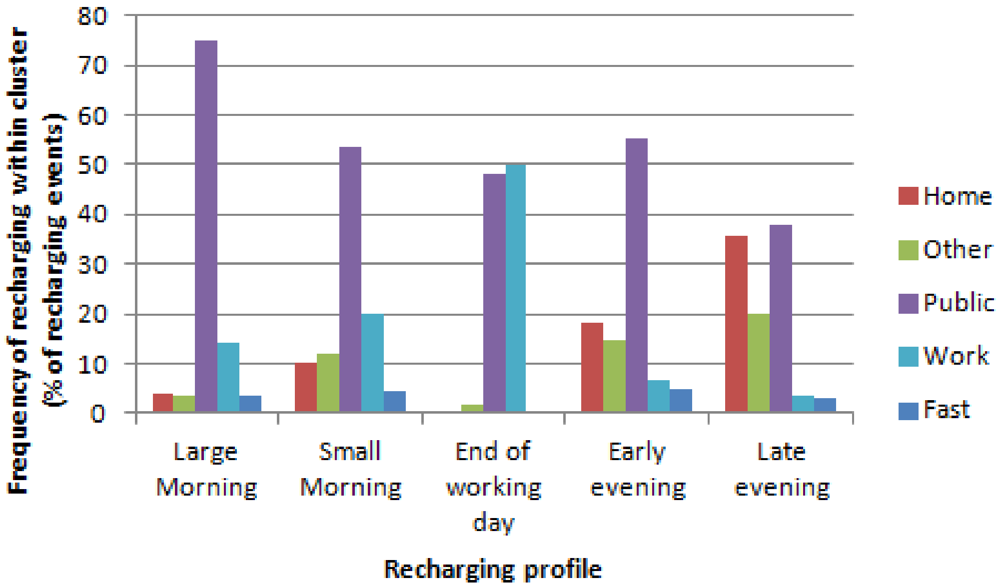

Figure 5-7: *Proportion of recharging by location in each cluster (each cluster totals 100%)*

Publically available recharging infrastructure, for all recharging profiles except the end of working day profile, was the most frequently used recharging location and accounted for 75% of the recharging events in the large morning, 53% of small morning, 48% of end of working day, 55% of early evening and 38% of late evening recharging events.

The proportion of recharging taking place at Work was highest for the end of working day recharging profile, with 50% of recharging events, compared to only 4% of late evening profile recharging events. With large morning, small morning and early evening, the proportions at work were 14%, 20% and 7% respectively.

In contrast, Home recharging constituted 4% of recharging events for users allocated in the large morning profile and less than 1% of recharging events in the end of working day recharging profile. As expected, most recharging at Home to took place outside of working hours, with 18% of recharging events occurred at Home in the early evening and 36% of recharging events in the late evening recharging profile. Only 10% of the recharging events in the small morning profile took place at home. By way of comparison, over 90% of recharging events took place at home in the MINI E trial. This was expected because MINI E drivers had very limited options, with no official non-domestic recharging network installed (BMW Group, 2011).

This recharging scenario was theorised by Mullan *et al.* (2011), Wang *et al.* (2011) and Kang and Recker (2009). On the other hand, in the CABLED trial, home recharging accounted for 62% of the total recharging events. Users had access to 36 recharging posts at 12 locations, 50% of which were associated with a parking fee during the CABLED study (Bruce *et al.*, 2012).

The SwitchEV trial users made more use of public recharging infrastructure than either CABLED or MINI E. The thematic analysis results indicate that the NE PiP network contained conveniently located recharging infrastructure in central Newcastle. The absence of an out of pocket cost for using the NE PiP network also made the non-domestic recharging infrastructure desirable. Therefore drivers were influenced to recharge at public infrastructure when strictly it was not required for them to complete their daily trips (Higgins *et al.*, 2012).

5.5. Large Morning Recharging Profile

Figure 5-8 illustrates the frequency of events by location for users allocated to the large morning recharging profile.

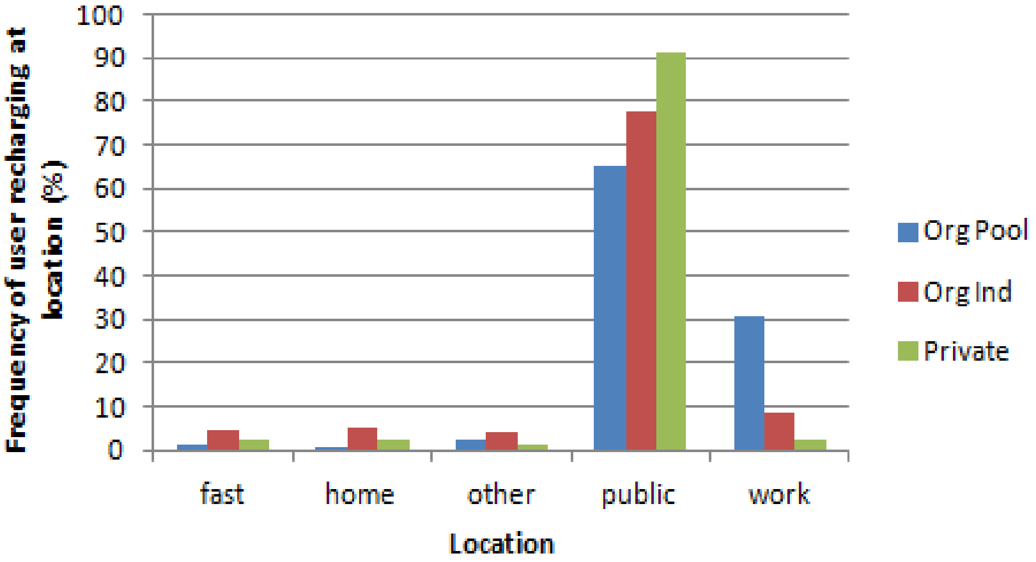

Figure 5-8: Large morning profile recharging events by location (each user type totals 100%)

92% of Private user, 77% of Organisation Individual and 65% of Organisation Pool recharging events took place at public locations. 31% of Organisation Pool users recharging took place at work. Recharging at Other locations was less than 4% for all user types. Figure 5-9 shows the usage of public infrastructure by large morning recharging profile users.

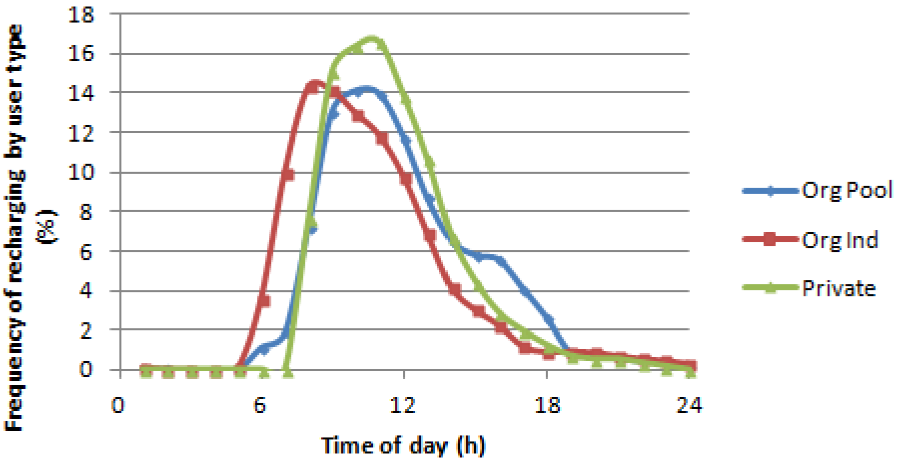

Figure 5-9: *Large morning recharging profiles at public locations by user type (each user type totals 100%)*

It can be seen that all recharging frequency peaks for large morning users were less than 17. The Organisation Pool user peak was 14% of recharging frequency, which occurred between 09:00h and 10:00h, whilst the Private user peak, constituting 17% of demand, occurred later in the day between 10:00h and 11:00h. For Organisation Individual users, the peak of 14% took place between 07:00h and 08:00h. 3% of Organisation Pool recharging, 14% of Organisation Individual recharging and <1% of Private user recharging frequency at public recharging infrastructure took place during the off-peak hours.

	Correlation coefficient (p-value)		
	Private	Org Ind	Org Pool
Private	1.00(<0.00)	0.84 (<0.00)	0.98 (<0.00)
Org Ind		1.00(<0.00)	0.85 (<0.00)
Org Pool			1.00(<0.00)

Table 5-2: Large morning recharging profile correlation coefficients between recharging profiles at public recharging infrastructure

As seen in Table 5-2, all user types following the large morning recharging profile made use of the public recharging infrastructure in a similar way. The recharging demand at work for users following the large morning profile is illustrated in Figure 5-10.

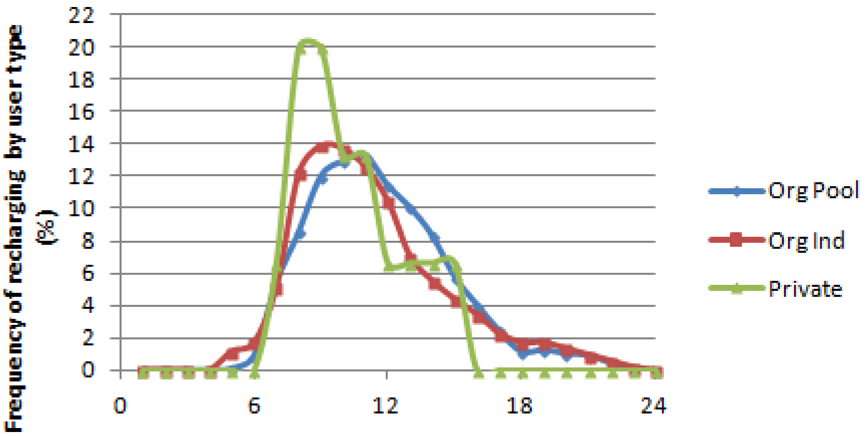

Figure 5-10: Large morning work recharging profiles by user type (each user type totals 100%)

Recharging at work for all users peaked before midday. For private and Organisation Individual users, this was expected, as it indicates that the users plug-in their vehicles up-on arriving at work, having commuted from home. For pool users, this peak illustrates that these vehicles were taken home and driven into work on a morning. Private users had two consecutive peak hours of recharging demand. 40% of recharging occurred in between 07:00h and 09:00h. The recharging profile of Private users was based on the two users assigned to this cluster. A smaller peak of 14% was observed for the Organisation Individual users, between 08:00h and 09:00h. A peak recharging frequency of 13% between 10:00h and 11:00h was observed for the Organisation Pool users. Recharging off-peak accounted for 6% of Organisation Pool user, 8% of Organisation Individual and 7% of Private user recharging frequency at work. The correlation coefficients for recharging at work locations by user type are shown in Table 5-3.

	Correlation coefficient (p-value)		
	Private	Org Ind	Org Pool
Private	1.00(<0.00)	0.94 (<0.00)	0.86 (<0.00)
Org Ind		1.00(<0.00)	0.96 (<0.00)
Org Pool			1.00(<0.00)

Table 5-3: Large morning recharging profile correlation coefficients between recharging profiles at work recharging infrastructure

This indicates that all users following the large morning recharging profile used the work recharging infrastructure in a statistically similar way. The recharging at work and public posts was similar for all user types.

5.6. Small Morning Recharging Profile

The recharging demand for small morning profile users by user type at each location can be seen in Figure 5-11.

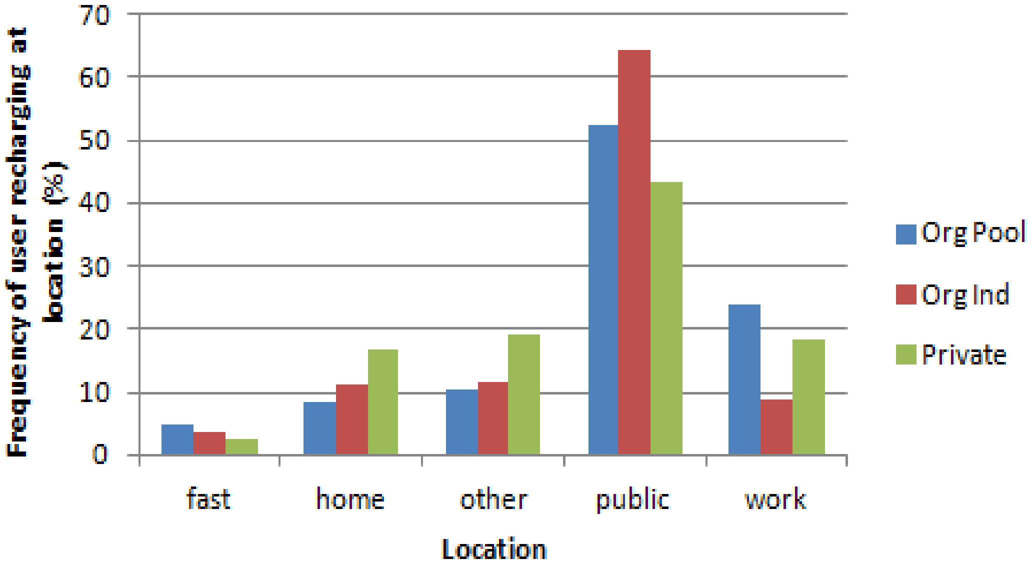

Figure 5-11: Small morning recharging demand by location for each user type (each user type totals 100%)

Again, similar to the large morning profile users, public recharging locations were the most frequently used by small morning recharging cluster with 52% of Organisation Pool, 64% of Organisation Individual and 43% of Private user recharging events. 8% of Organisation Pool, 11% of Organisation Individual and 17% of Private users recharging events took place at home. Workplace recharging accounted for 24% of Organisation Pool and 18% of Private users recharging events. This was more than Organisation Individuals, with 9%.

Figure 5-12 shows the small morning user recharging profiles at public locations.

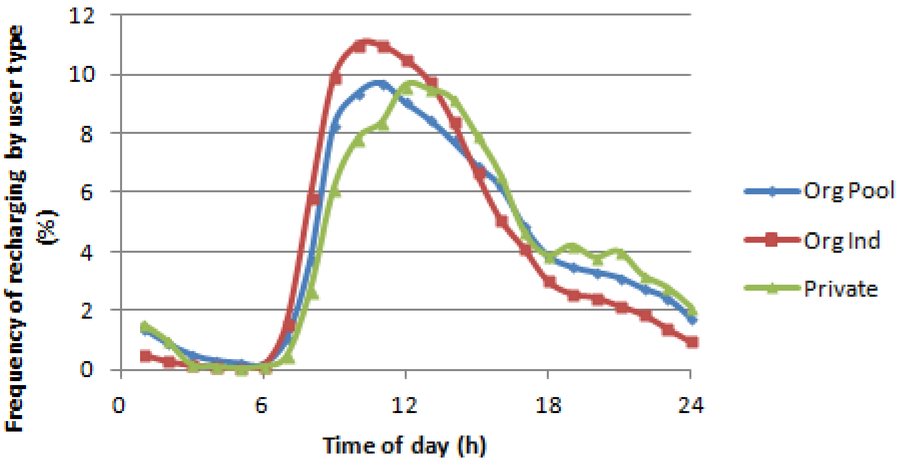

Figure 5-12: *Small morning public recharging profiles by user type (each user type totals 100%)*

All users’ recharging demand at public posts peaked before 12:00h. Organisation Pool user recharging peaked between 10:00h and 11:00h, at 10% of recharging frequency whilst Organisation Individual users’ peak demand occurred an hour earlier, between 09:00h and 10:00h at 11%. Private users peaked later in the day, between 11:00h and 12:00h, when 10% of the recharging frequency took place. 5% of Organisation Pool, 3% of Organisation Individual and 4% of Private user recharging frequency occurred during the off-peak hours.

Table 5-4 shows the correlation coefficients between the user types at public recharging locations, indicating that to a statistical confidence of 95%, usage of public recharging infrastructure did not vary significantly between user types.

	Correlation coefficient (p-value)		
	Private	Org Ind	Org Pool
Private	1.00(<0.00)	0.91 (<0.00)	0.96 (<0.00)
Org Ind		1.00(<0.00)	0.98 (<0.00)
Org Pool			1.00(<0.00)

Table 5-4: Small morning recharging profile correlation coefficients between recharging profiles at public recharging infrastructure

The recharging profiles for small morning users at work locations are illustrated in Figure 5-13.

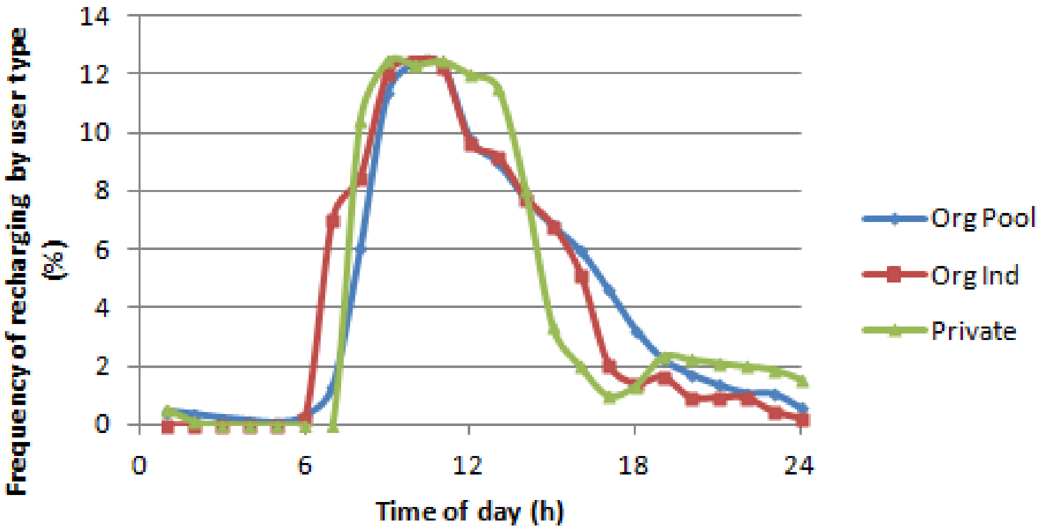

Figure 5-13: *Small morning work recharging profiles by user type (each user type totals 100%)*

It can be seen that the recharging at work also peaked before 12:00h for all user types. All user groups peaked at marginally above 12% of total recharging frequency at work but occurred at different times, namely between 10:00h and 11:00h for private, 09:00h and 10:00h for Organisation Individual and 09:00h and 10:00h for Organisation Pool users. The percentage of recharging frequency taking place during the off-peak hours was 3%, 7% and 1% respectively for Organisation Pool, Organisation Individual and Private users.

	Correlation coefficient (p-value)		
	Private	Org Ind	Org Pool
Private	1.00(<0.00)	0.91 (<0.00)	0.92 (<0.00)
Org Ind		1.00(<0.00)	0.94 (<0.00)
Org Pool			1.00(<0.00)

Table 5-5: Small morning recharging profile correlation coefficients between recharging profiles at work recharging infrastructure

As indicated in Table 5-5, there were no statistically significant differences between the recharging demand profiles at work for users allocated to the small morning recharging profile.

The home recharging profiles for small morning recharging profile users are illustrated in Figure 5-14.

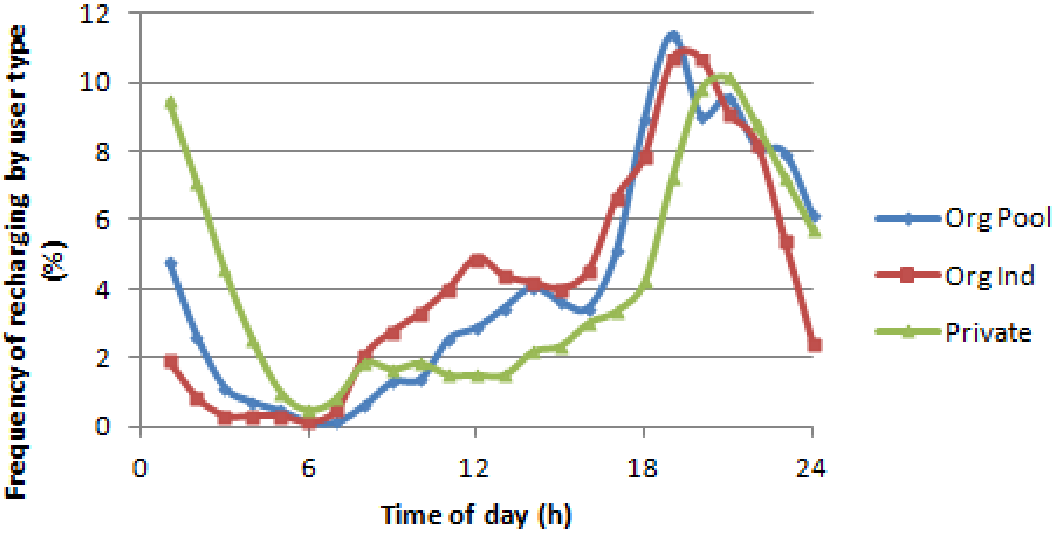

Figure 5-14: Small morning home recharging profiles by user type (each user type totals 100%)

For the small morning peak profile, Organisation Pool, Organisation Individual and Private users carried out most home recharging after 18:00h, with peak frequencies of 11% between 18:00h and 19:00h, 11% between 18:00h and 19:00h and 10% between 20:00h and 21:00h respectively. Off-peak recharging accounted for 10% of Organisation Pool user recharging and 5% of Organisation Individual recharging frequency, which was subsequently lower than 26% of Private user recharging at home, as expected. The correlation coefficients for the recharging profiles at home by the three user types are shown in Table 5-6 and indicate that there were no significant differences between the home recharging profiles for different user types in the cluster.

	Correlation coefficient (p-value)		
	Private	Org Ind	Org Pool
Private	1.00(<0.00)	0.56 (0.01)	0.77 (<0.00)
Org Ind		1.00(<0.00)	0.89 (<0.00)
Org Pool			1.00(<0.00)

Table 5-6: Small morning recharging profile correlation coefficients between recharging profiles at home recharging infrastructure

Recharging profiles for other locations by small morning users are illustrated in Figure 5-15.

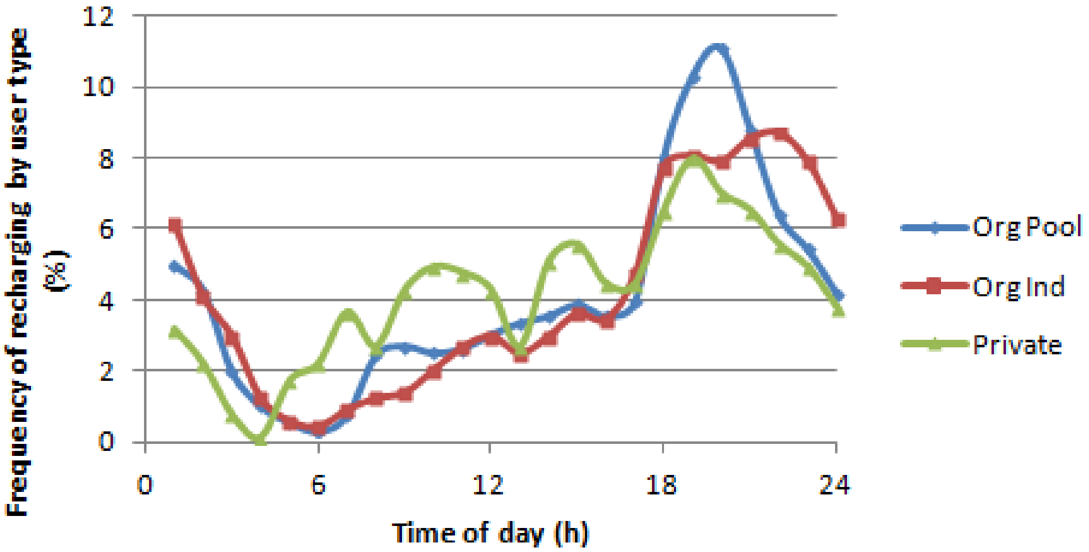

Figure 5-15: *Small morning recharging profiles at other locations by user type (each user type totals 100%)*

The largest peak in recharging at other locations, for Organisation Pool users, occurred between 19:00h to 20:00h, with 11% of demand. Private user recharging frequency peaked at other locations at 8% and was earlier, between 18:00h and 19:00h and Organisation was later, between 21:00 and 22:00h, with 9% of the total frequency. 14% of Organisation Pool, 17% of Organisation Individual and 14% of Private user recharging frequency occurred during the off-peak hours at other locations.

	Correlation coefficient (p-value)		
	Private	Org Ind	Org Pool
Private	1.00(<0.00)	0.69 (<0.00)	0.79 (<0.00)
Org Ind		1.00(<0.00)	0.90 (<0.00)
Org Pool			1.00(<0.00)

Table 5-7: Small morning recharging profile correlation coefficients between recharging profiles at other recharging infrastructure

The recharging profiles at other locations were not statistically significantly different between user types, as seen in Table 5-7.

5.7. End of Working Day Recharging Profile

Figure 5-16 shows the frequency of use of each of the recharging locations observed for the end of working day users.

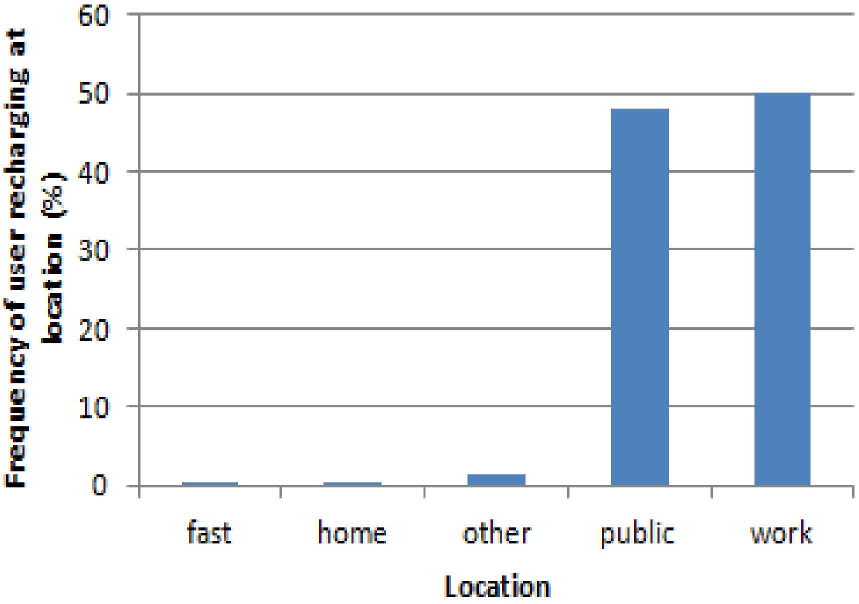

Figure 5-16: End of working day recharging use by location

Recharging events were distributed fairly equally between public and work, accounting for 50% and 48% respectively. Less than 1% of recharging events took place at home. This was the only group of drivers for which public recharging locations were not the most frequently used recharging location. This is because this profile consisted largely of Organisation Pool users with dedicated workplace access, whereby vehicles would be out on organisation business during the day and recharged at the end of the day at the work depot/car park.

The recharging demand profiles at work and public locations for Organisation Pool users following the end of working day recharging profile are illustrated in Figure 5-17.

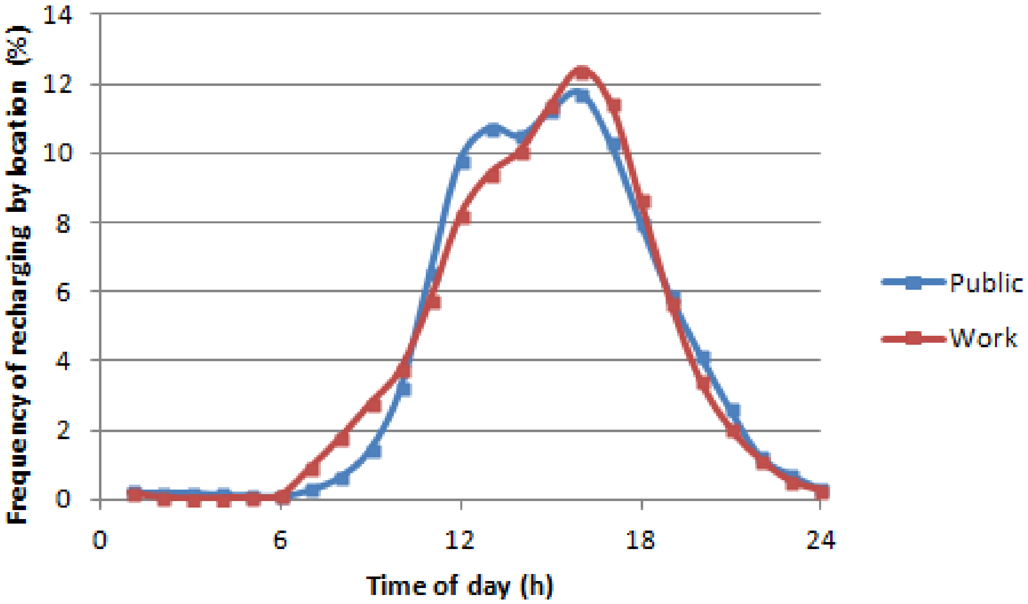

Figure 5-17: End of working day recharging profiles by location (each user type totals 100%)

It can be seen that, at both location types, the recharging demand peaked before 18:00h with the Organisation Pool users at the end of working day with peak frequency of 12% between 15:00h and 16:00h at public recharging infrastructure and a similar peak of 12% at the same time at work. Both profile shapes were characterised in addition to the peaks in the late afternoon with smaller recharging demand on a morning. 1% of recharging frequency at public locations and 2% at work took place during the off-peak hours.

The correlation coefficient between work and public recharging profiles for the Organisation Pool users at work and other locations following this profile was 0.99 (p=0.00).Users allocated to this recharging profile therefore made use of public and work recharging infrastructure at similar times of day.

5.8. Early Evening Recharging Profile

This section describes the characteristics of the early evening recharging profile. The percentage of recharging events at each location by user type can be seen in Figure 5-18.

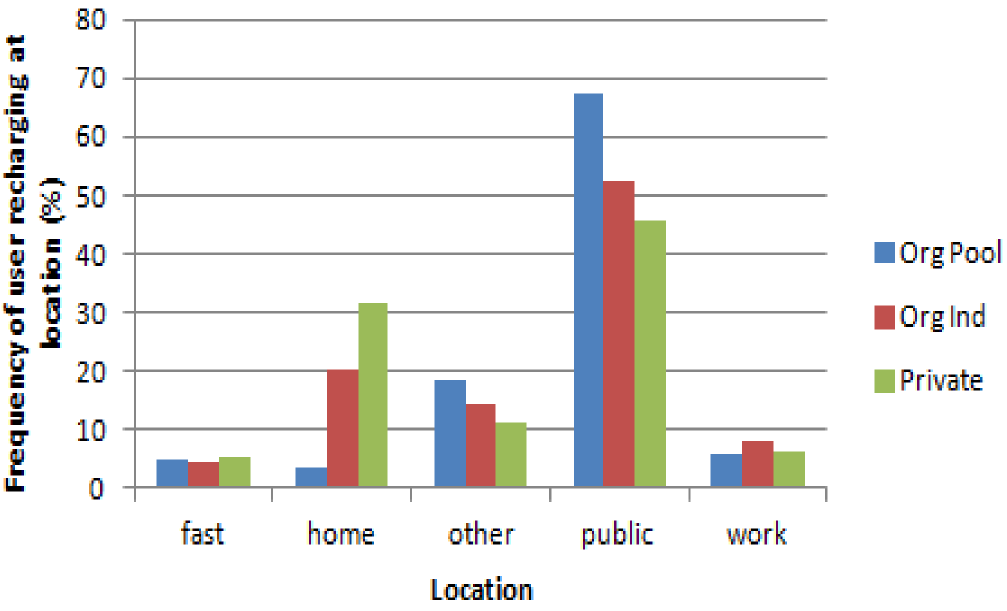

Figure 5-18: Frequency of recharging events per location by user type for early evening recharging profile users (each user type totals 100%)

Public recharging infrastructure was used most frequently by all user types, with 67%, 52% and 45% for Organisation Pool, Organisation Individual and Private users respectively. Home and other locations were also utilised. Private users recharging events at home and other locations accounted for 32% and 11% respectively. For Organisation Individual users recharging event took place at home and other locations respectively at 20% and 15%. For Organisation Pool user recharging, 4% was recorded at home. However, more frequent use was made of other recharging locations at 18%.

Figure 5-19 shows the recharging profiles, by user type, for home recharging by early evening profile users.

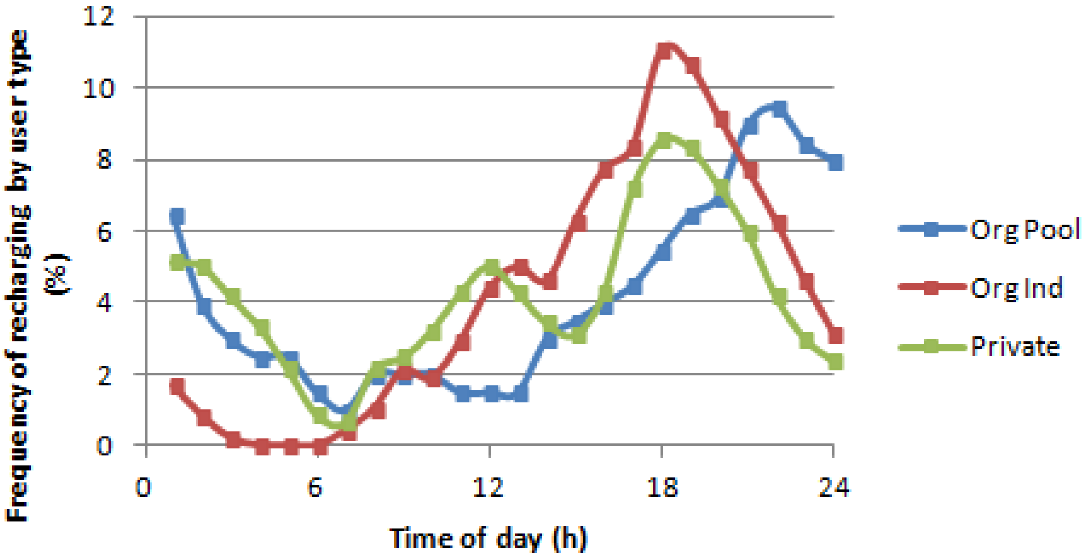

Figure 5-19: Early evening user home recharging profiles by user type (each user type totals 100%)

All three recharging demand peaks at home between 18:00h and 24:00h with peak frequency of 9%, 11% between 17:00h and 18:00h and 9% between 21:00h and 22:00h for private, Organisation Individual and Organisation Pool users respectively.

At home, 20% of Organisation Pool, 3% of Organisation Individual and 21% of Private user recharging frequency was during the off-peak hours. The correlation co-efficient for the recharging demand at home locations by user type are given in Table 5-8, where all three user types recharging demands were statistically significantly correlated.

	Correlation coefficient (p-value)		
	Private	Org Ind	Org Pool
Private	1.00(<0.00)	0.79 (<0.00)	0.44 (0.03)
Org Ind		1.00(<0.00)	0.53 (0.01)
Org Pool			1.00(<0.00)

Table 5-8: Early evening recharging profile correlation coefficients between user group profiles for home recharging

Figure 5-20 illustrates the early evening user recharging profiles at public recharging locations, showing peak frequencies for Private users occurring between 17:00h and 18:00h (9%), and an hour later between 18:00h and 19:00h for Organisation Individual and Organisation Pool users with 7% and 8% respectively.

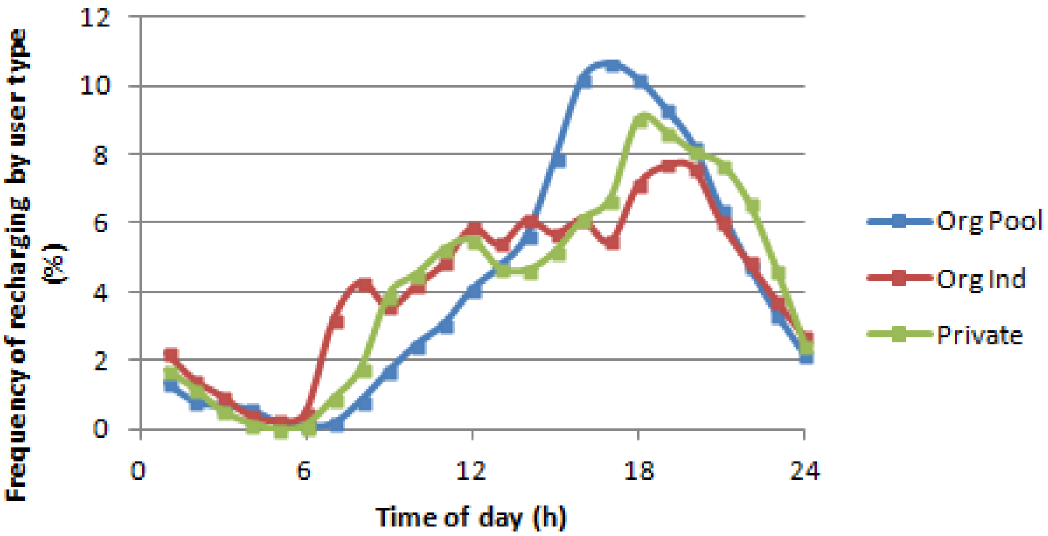

Figure 5-20: Early evening user public recharging profiles by user type (each user type totals 100%)

4% of Organisation Pool, 9% of Organisation Individual and 5% of Organisation Pool, Organisation Individual and Private user recharging frequency occurred during the off-peak hours.

Table 5-9 presents correlation coefficients for the early evening recharging profile for public recharging infrastructure usage by each user type.

	Correlation coefficient (p-value)		
	Private	Org Ind	Org Pool
Private	1.00(<0.00)	0.93 (<0.00)	0.48 (0.03)
Org Ind		1.00(<0.00)	0.85 (<0.00)
Org Pool			1.00(<0.00)

Table 5-9: Early evening recharging profile correlation coefficients between recharging profiles at public recharging infrastructure

This indicates that there was no statistically significant difference in the recharging demand profiles at public locations for different user types within the early evening cluster. The early evening user recharging profiles at other locations are illustrated in Figure 5-21 with Private user peak frequency occurring between 19:00h and 20:00h, during which 10% of recharging took place. At other locations, Organisation Pool users recharging peak occurred between 18:00h and 19:00h with 10% of recharging frequency whilst Organisation Individual user peak was earlier with the recharging frequency reaching 12%, between 17:00h and 18:00h.

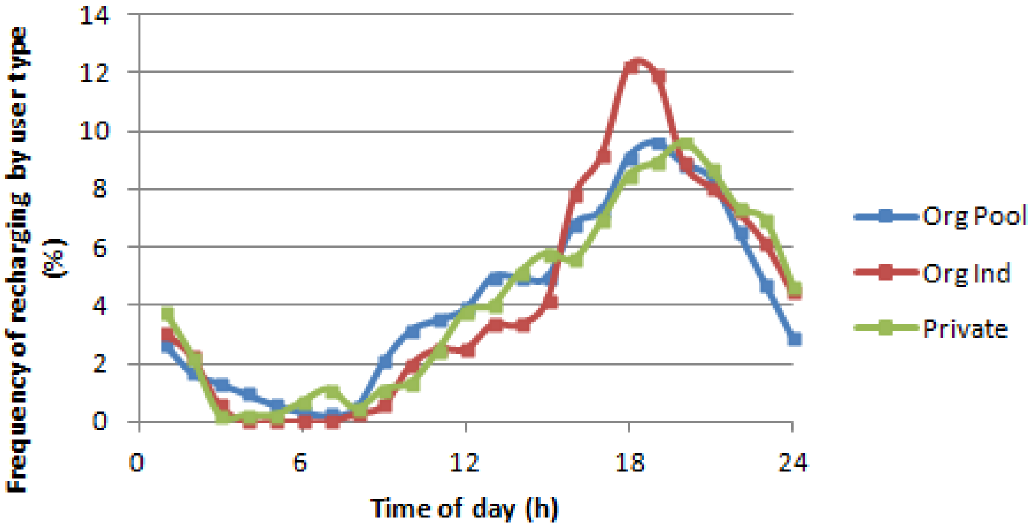

Figure 5-21: Early evening user other locations recharging profiles by user type (each user type totals 100%)

Recharging at Other locations could present a problem for future recharging management as these will not have timers attached. This highlights the importance of ensuring that EV users have access to dedicated home recharging infrastructure were possible. Off-peak recharging accounted for 8%, 6% and 9% of Organisation Pool, 6% of organisation single and 9% of Organisation Pool user recharging frequency respectively.

The correlation coefficients for usage of other recharging infrastructure by each user type following the early evening recharging profile are presented in Table 5-10. Given all recharging profiles correlation are close to unity, the three user types in the early evening cluster made use of other recharging locations in a similar way.

	Correlation coefficient (p-value)		
	Private	Org Ind	Org Pool
Private	1.00(<0.00)	0.95 (<0.00)	0.94 (0.03)
Org Ind		1.00(<0.00)	0.96 (<0.00)
Org Pool			1.00(<0.00)

Table 5-10: Early evening recharging profile correlation coefficients between recharging profiles at other recharging locations

Overall, the recharging profiles by user type in this cluster were statistically significantly similar at all recharging locations. Given the similarity of home and other recharging, it can be concluded that drivers in this cluster recharged their vehicles at similar times and in similar locations.

5.9. Late Evening Recharging Profile

The late evening recharging profile was the smallest cluster in this study in terms of total user allocation. The frequency of recharging events for users following the late evening recharging profile at each location can be seen in Figure 5-22.

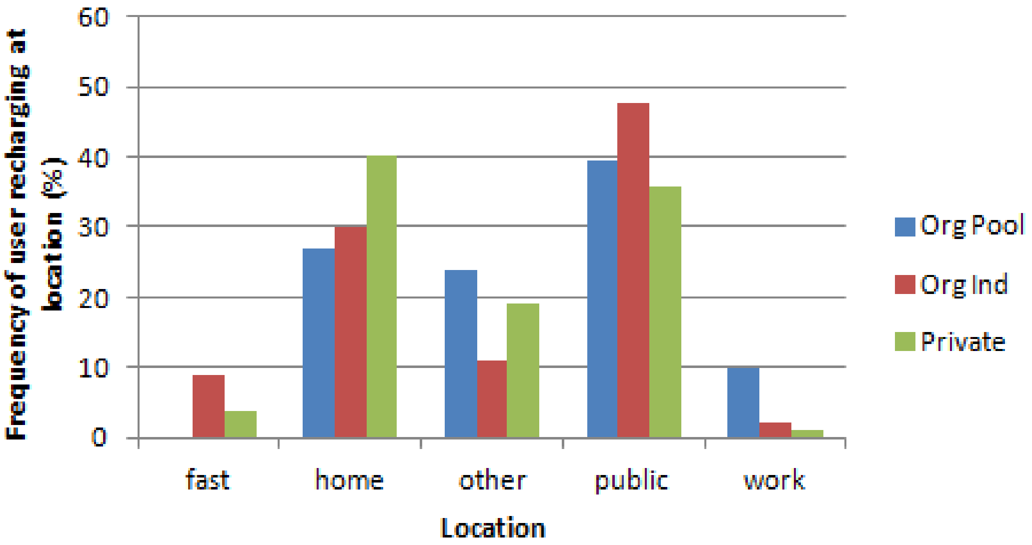

Figure 5-22: Late evening user recharging demand by user type at each location (each user type totals 100%)

As one would expect, more home recharging was recorded in this cluster than any other. This is because the time of the peak demand is likely to be outside the working day of most participants. 27% of Organisation Pool, 30% of Organisation Individual and 40% of Private users recharging events took place at home. Furthermore, 24% of Organisation Pool users, 11% of Organisation Individual users and 19% of Private users recharged their vehicles at other locations.

Home was the most frequent recharging location for the Private users. This was the only recharging profile in which any of the user types recharging was primarily at home. Public was the most frequent location for Organisation Individual and Organisation Pool users, with 48% and 40% respectively of recharging events being recorded at these locations. 36% of Private users recharging events took place at public locations.

Figure 5-23 shows the home recharging profiles for user types following the end of working day recharging profile.

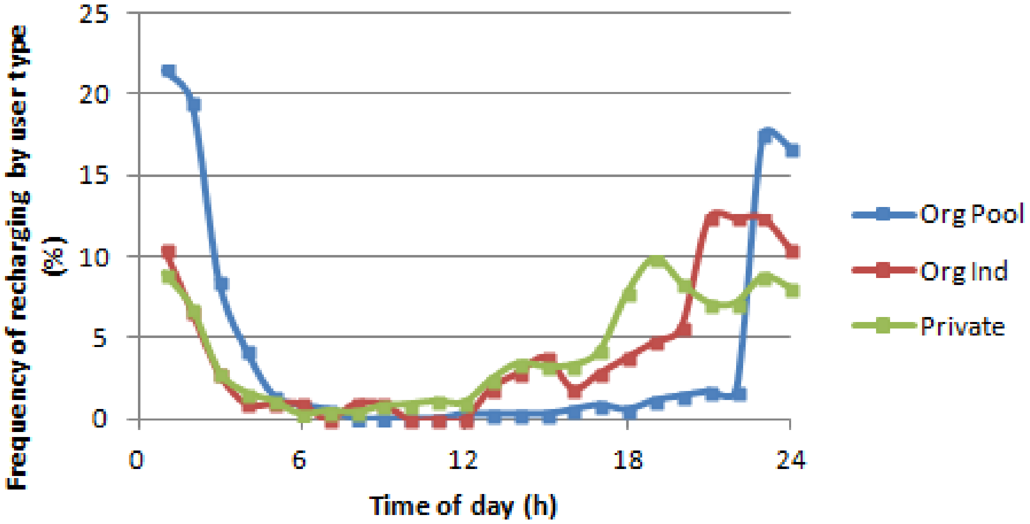

Figure 5-23: End of working day user home recharging profiles by user type (each user type totals 100%)

All three user types recharging frequency at home peaked between 18:00h and 24:00h. The Private users peaked between 18:00h and 19:00h at 10%. 22% of Private user recharging took place off-peak. The Organisation Individual users peaked between 21:00h and 22:00h, where 12% of recharging frequency was recorded. 23% of Organisation Individual user home recharging was during the off-peak hours. The Organisation Pool users had both the latest in the day and the largest relative peak, constituting 18% of recharging frequency between 22:00h and 23:00h. 57% of recharging by Organisation Pool users at home took place off-peak. Three of the four Organisation Pool user vehicles followed this profile. It is expected that these users were using the timer functionality of their home recharging points to delay recharging into the off-peak hours. Table 5-11 illustrates the correlation coefficient for home recharging by user type.

	Correlation coefficient (p-value)		
	Private	Org Ind	Org Pool
Private	1.00(<0.00)	0.82 (<0.00)	0.55 (0.01)
Org Ind		1.00(<0.00)	0.62 (<0.00)
Org Pool			1.00(<0.00)

Table 5-11: Late evening recharging profile correlation coefficients between recharging profiles at home recharging locations

No significant difference was found between the three user types in the late evening recharging profile for recharging at home. The recharging demand for end of working day users at other locations can be seen in Figure 5-24.

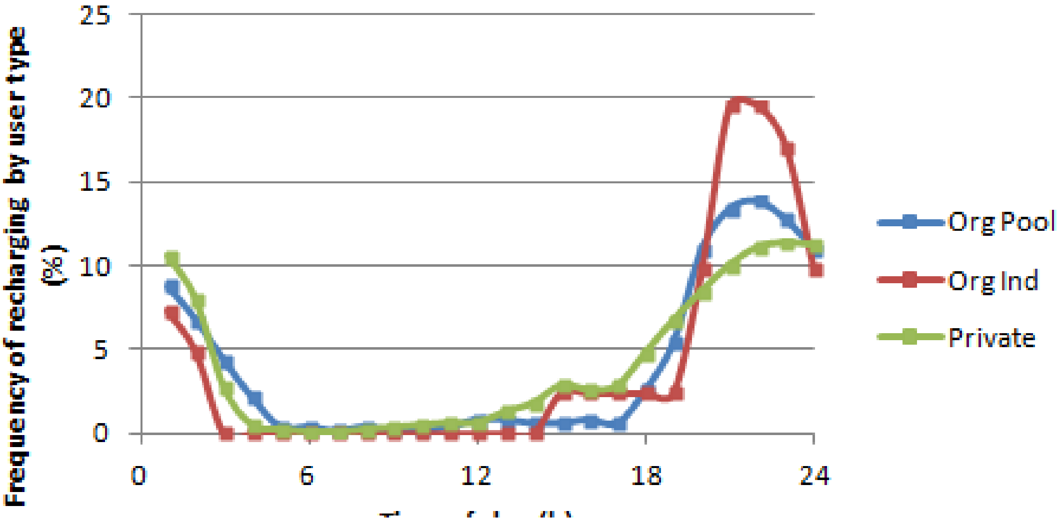

Figure 5-24: Late evening recharging profiles at other locations by user type (each user type totals 100%)

All peaks in frequency at other locations occurred between 18:00h and 24:00h. The largest relative peak was for Organisation Individual users, whereby 20% of recharging occurred between 20:00h and 21:00h. 5% of Organisation Individual recharging at public locations took place during the off-peak hours. Private users recharging demand peaked at 11%, between 22:00h and 23:00h. Off-peak recharging accounted for 21% of Private user recharging at public locations. Organisation Pool users recharging peaked between 22:00h and 23:00h, at 18% of total recharging frequency. 7% of Organisation Pool user recharging occurred during the off-peak hours.

The correlation coefficients between the user types at public recharging locations for users following the late evening recharging profile can be seen in Table 5-12.

	Correlation coefficient (p-value)		
	Private	Org Ind	Org Pool
Private	1.00(<0.00)	0.88 (<0.00)	0.95 (0.01)
Org Ind		1.00(<0.00)	0.94 (<0.00)
Org Pool			1.00(<0.00)

Table 5-12: Late evening recharging profile correlation coefficients between recharging profiles at public recharging locations

There was no significant difference between the recharging profiles of the three user types at other locations. The recharging profiles for end of working day users at the public recharging infrastructure are presented in Figure 5-25.

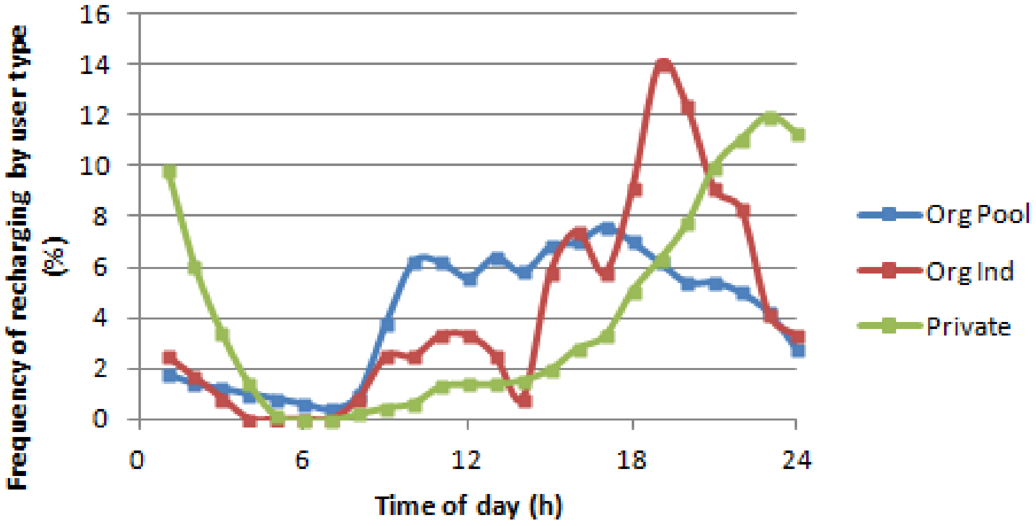

Figure 5-25: Late evening recharging profiles at public locations by user type (each user type totals 100%)

The end of working day users of made differing use of public recharging infrastructure. Organisation Pool had a relatively small peak in peak frequency of 8%, between 16:00h and 17:00h. Organisation Individual vehicles saw a small peak at the end of the working day. This occurred between 15:00h and 16:00h and constituted 7% of recharging frequency. A larger peak, of 14%, occurred later in the day between 18:00h and 19:00h. The Private users recharging peaked between 22:00h and 23:00h, at 12% of recharging frequency. Off-peak recharging accounted for 7% of Organisation Pool user recharging, 5% of Organisation Individual recharging and 21% of Private user recharging at public locations.

Table 5-13 presents the correlation coefficients between user types at home for users following the late evening recharging profile.

	Correlation coefficient (p-value)		
	Private	Org Ind	Org Pool
Private	1.00(<0.00)	0.51 (0.01)	0.11 (0.62)
Org Ind		1.00(<0.00)	0.66 (<0.00)
Org Pool			1.00(<0.00)

Table 5-13: Late evening recharging profile correlation coefficients between recharging profiles at home recharging locations

There were significant differences in the public recharging infrastructure usage in this cluster between Private users and Organisation Pool users. There was no significant difference between the other two user types usage of public recharging infrastructure. The Private user and Organisation Individual recharging peaks could be delayed using smart meters (McHenry, 2013; Tie and Tan, 2013; Usman and Shami, 2013).

5.10. **Comparison of Recharging Demand Profiles by Location**

This section compares the recharging profiles from the previous discussion between different clusters to identify key distinguishing features between different types of recharging profiles and how users in different clusters interact with the recharging infrastructure. Figure 5-26 shows how the recharging profiles vary for each of the clusters at Home.

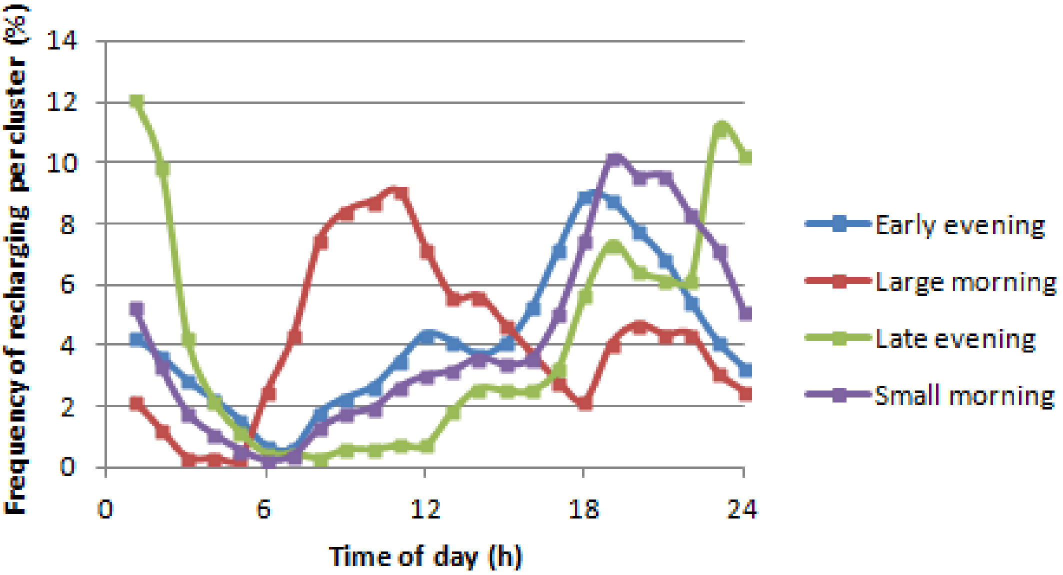

Figure 5-26: Home recharging profiles by cluster (each cluster totals 100%)

The correlation coefficients between the recharging profiles for recharging demand at home locations can be seen in Table 5-14.

	Correlation coefficient (p-value)			
	Large Morning	Small Morning	Early evening	Late Evening
Large morning	1.00(<0.00)	0.06 (0.79)	-0.05 (0.81)	-0.22 (0.30)
Small morning		1.00(<0.00)	0.88 (<0.00)	0.65 (0.00)
Early evening			1.00(<0.00)	0.46 (0.02)
Late evening				1.00(<0.00)

Table 5-14: Correlation coefficients between users following different recharging profiles for recharging at home

It can be ascertained that there was no significant difference between the recharging profiles by time of day at home locations, with the exception of the large morning cluster. The home recharging profile for users in this cluster was significantly different from the home recharging profiles of users in all other clusters.

Home recharging provides an ideal opportunity for technologies such as smart meters to balance loads on power grids by delaying recharging. For the large morning profile, there may be a need for recharging demand management strategies due to peak in demand occurring before midday. Alternatively, pricing signals could be used to shift this recharging demand either to the night before or the upcoming evening off-peak period (Hedegaard *et al.*, 2012; McHenry, 2013; Oliveira *et al.*, 2013).The other recharging profiles can be seen in Figure 5-27.

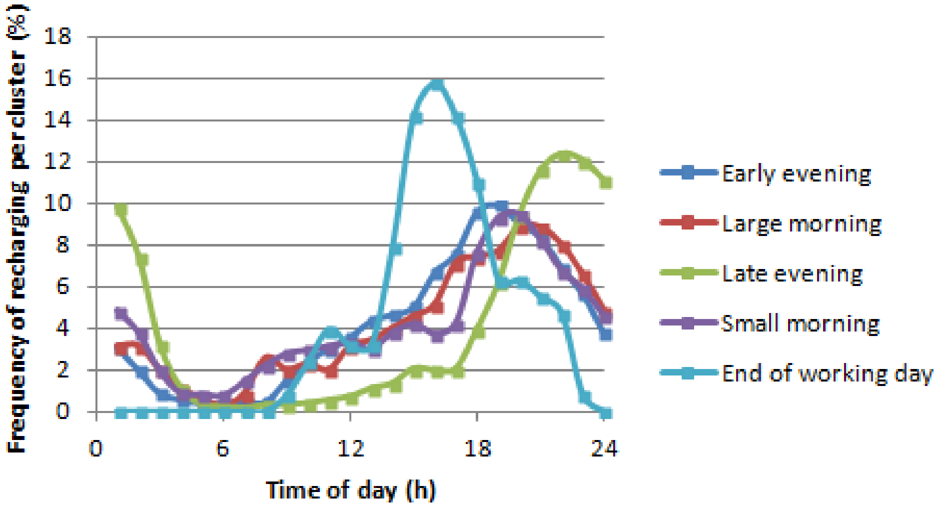

Figure 5-27: Other recharging profiles by cluster (each cluster totals 100%)

With the exception of the end of working day recharging profile, all other profiles recharging demand peaks at other locations occurred after 18:00h. Table 5-15 presents the correlation coefficients for the recharging demand by time of day at other locations between the five overall recharging profiles.

	Correlation coefficient (p-value)				
	Large Morning	Small Morning	End of working day	Early evening	Late evening
Large morning	1.00(<0.00)	0.93(<0.00)	0.58(0.01)	0.95(0.00)	0.68(<0.00)
Small morning		1.00(<0.00)	0.37(0.08)	0.91(<0.00)	0.71(<0.00)
End of working day			1.00(<0.00)	0.69(<0.00)	-0.06(0.77)
Early evening				1.00(<0.00)	0.50(0.01)
Late evening					1.00(<0.00)

Table 5-15: Correlation coefficients between users following different recharging profiles for recharging at other locations

This means that, with the exception of the end of working day users, none of the recharging profiles at other locations were significantly different. End of working day was significantly different from the late evening and small morning users.

Figure 5-28 illustrates the public recharging profiles for all clusters.

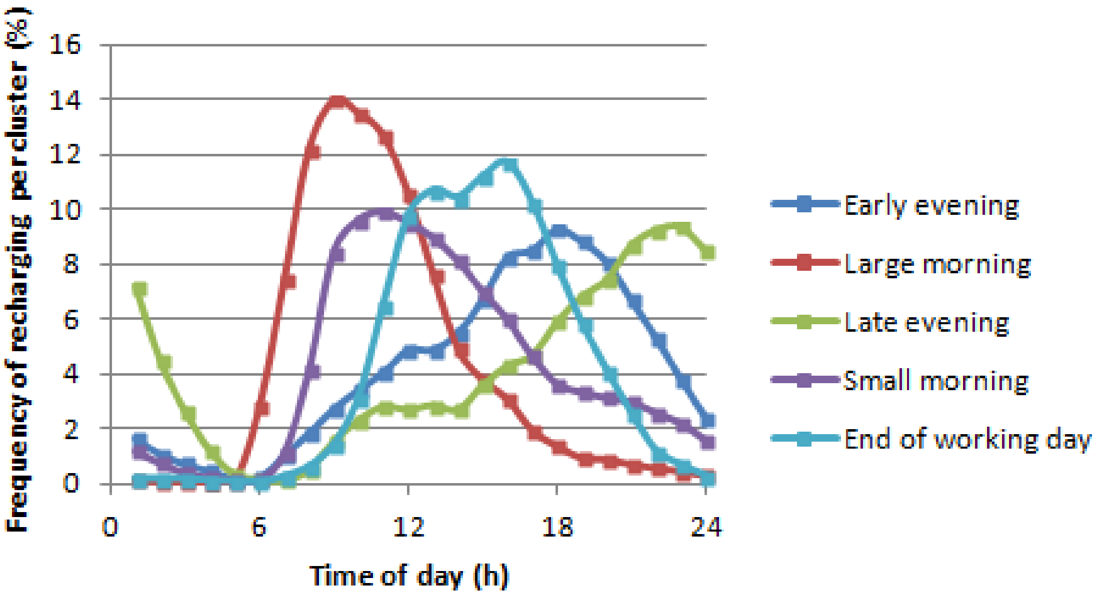

Figure 5-28: Public recharging profiles by cluster (each cluster totals 100%)

The correlation coefficients for the recharging demand by time of day at public recharging locations between the five overall recharging profiles can be seen in Table 5-16.

	Correlation coefficient (p-value)				
	Large Morning	Small Morning	End of working day	Early evening	Late evening
Large morning	1.00(<0.00)	0.76(<0.00)	0.20(0.36)	-0.09(0.68)	-0.37(0.06)
Small morning		1.00(<0.00)	0.69(0.00)	0.35(0.10)	-0.17(0.43)
End of working day			1.00(<0.00)	0.74(<0.00)	-0.01(0.99)
Early evening				1.00(<0.00)	0.49(0.01)
Late evening					1.00(<0.00)

Table 5-16 Correlation coefficients between recharging profiles at public locations

This implies that the users in the two evening clusters did not make significantly different use of public recharging infrastructure. This similarity was also observed between users in the two morning clusters. The end of working day cluster was similar to the small morning and early evening recharging profiles.

This suggests that each cluster requires technologies and management strategies with regard to recharging demand placed on the public recharging infrastructure. Users following the early and late evening recharging profiles could have their recharging delayed into off-peak hours.

Some users following the morning and end of working day recharging profiles may require the loads to be balanced throughout the working day rather than delayed into the off-peak hour. This is because many non-private vehicles have operation requirement that they are always recharging when they are parked at a recharging post. However, it is expected that some of these users are taking advantage of free parking spaces, so there is likely to be less public recharging demand if users accessed public recharging posts via a pay as you go mechanism (Schey *et al.*, 2012).The work recharging profiles for all clusters are illustrated in *Figure 5-29*.

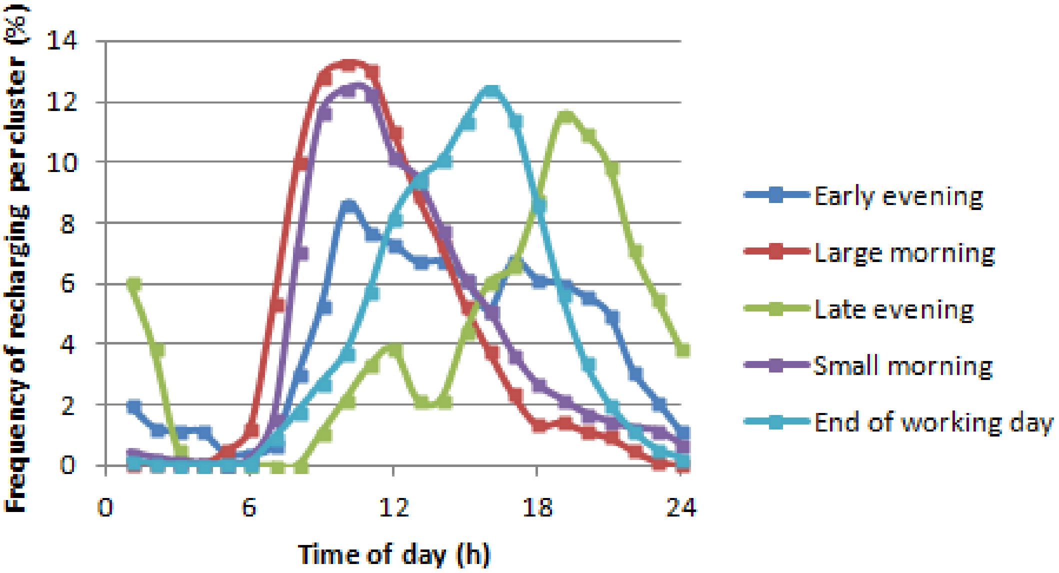

Figure 5-29: Work recharging profiles by cluster (each cluster totals 100%)

Table 5-17 illustrates the correlation coefficients for the recharging demand by time of day at other locations between the five overall recharging profiles.

	Correlation coefficient (p-value)				
	Large Morning	Small Morning	End of working day	Early evening	Late evening
Large morning	1.00(<0.00)	0.97(<0.00)	0.36(0.09)	0.63(<0.00)	-0.35(0.10)
Small morning		1.00(<0.00)	0.51(0.01)	0.77(<0.00)	-0.20(0.35)
End of working day			1.00(<0.00)	0.76(<0.00)	0.30(0.19)
Early evening				1.00(<0.00)	0.38(0.06)
Late evening					1.00(<0.00)

Table 5-17: Correlation coefficients between recharging profiles at work

Users following the large morning and small morning profiles made use of work recharging infrastructure in a similar way. This was expected as it reflects the morning commute. Users in all other overall cluster profiles show significant differences in terms of the peak demands and the relative size of the peaks.

There are also similarities overall between different clusters in terms of how recharging infrastructure was utilised. Usage of home and other recharging infrastructure was similar for all clusters in terms of the time of day of peaks and the relative size of the peaks. The similarity between home and other suggests that users who did not have a dedicated NE PiP home recharging post installed plugged their EVs into standard three pin sockets at domestic locations. Given that over 90% of SwitchEV users were employed full time, this is likely to be because all trial participants were at work during the day and return home on an evening and plug-in their EVs at a similar time.

For work recharging, there were some differences in the magnitude of peaks but they were again used in broadly the same way. Given that workplace recharging posts on site, and generally vehicles were recharging whenever they were at base, it is thought that the operational needs of a vehicle influenced the workplace recharging profiles. For example, end of working day recharging is likely to have been organisations where the EV is typically used for business purposes on a morning and early afternoon and then returns to the workplace.

Differences in public recharging usage could be explained by a combination of user attitudes to public recharging infrastructure and the membership access scheme for non-domestic recharging posts. Users with a public recharging post near their place of work are likely to be using the public recharging post as a parking space. This is especially likely for those working in the centre of Newcastle, which was considered to have abundant and conveniently located recharging infrastructure.

5.11. Summary of Key Findings from Recharging Profile Analysis

- **Five typical recharging profiles were identified**

Five recharging profiles were observed within the dataset. Based on the time of day and size of the recharging peak, these were; large morning, small morning, end of working day, early evening, late evening. The key characteristics of these profiles are illustrated in Table 5-18.

	Recharging profile				
	Large morning	Small morning	End of working day	Early evening	Late evening
Peak hour for recharging (h)	08:00h-09:00h	10:00h-11:00h	15:00h-16:00h	17:00-18:00h	22:00h-23:00h
Peak hour % recharging	13	9	12	9	10
% off-peak recharging	10	6	1	7	22
Total users	29	50	22	26	13
% Private users	9	26	0	35	30
% Org Ind users	47	30	0	19	5
% Org Pool users	9	42	30	14	5

Table 5-18: Summary statistics for the five recharging profiles

- **User type had a significant impact on recharging profile allocation**

User type was found to have an influence on the likelihood of a user appearing in a particular cluster. Overall, Organisation Pool users were most likely to recharge either on a morning or at the end of the working day. Private users were most likely to follow one of the two evening recharging profiles. Organisation Individual users were most likely to recharge on a morning.

- **User types following the same recharging profile used recharging infrastructure in statistically similar ways**

For any given recharging profile, there were typically no significant differences in the usage of recharging infrastructure by location between users allocated to the cluster, regardless of user type. When managing this demand, one strategy is required per recharging profile.

- **Further energy management strategies are required if total off-peak recharging is to be increased**

Between 1% and 22% of recharging frequency took place off-peak depending on the recharging profile. It is recommended that financial incentives and smart meters are installed at both home and work locations to manage recharging demand. Furthermore, pricing strategies for public recharging infrastructure should be implemented to manage daytime recharging demand.

6. Analysis of User Interventions

6.1. **Introduction**

It was found in Chapter 5 that SwitchEV participants, regardless or user type or recharging infrastructure access, did not complete the majority of their recharging during the off-peak periods. This could lead to overload of power grids in the EV market grows at projected rates. Therefore, there is a need to understand whether financial incentives can be effective demand management tools in a region with a high density of non-domestic recharging infrastructure with membership access. Furthermore, the results of the previous chapter highlight the need to understand how behaviour could be modified if the financial incentives alone are not effective.

This chapter describes the results of the intervention process and begins with a review of the drivers taking part in the interventions. These users are then compared to the non-intervention participants and a control group of users with the similar recharging profile and user type. Subsequently, the control group is compared to the intervention group to prove that a robust and rigorous comparison is being made between users.

This control group of users is then analysed, to quantify whether differences in recharging behaviour by both location and time of day are statistically significant.

This begins by quantifying the overall change in percentage points of the duration of off-peak recharging before and after the intervention at each location. Firstly, this was for all locations for all users and secondly at home and work locations for users of these locations only. An analysis of the off-peak recharging on a month by month basis and the changes in carbon content pre- and post-intervention are presented. The aim of this control group analysis was to determine whether there was a general change in recharging behaviour for non-intervention participants throughout their trial, thus allowing the extent to which any changes in behaviour for the intervention participants could be quantified and attributed to the intervention and which changes could be explained by other factors.

This analytical process was repeated for the intervention participants. These are compared to the results of the control group to assess the effectiveness of the interventions. Results of a test to determine whether total duration of post-intervention recharging was linked to the percentage point change in off-peak recharging during the post-intervention period are also presented. The responses of the drivers to both the open ended and post-trial questions as outlined in the methodology are then analysed. This chapter concludes with a summary of the key findings of the intervention study.

6.2. **Intervention Participants**

In total 21 SwitchEV users agreed to take part in the intervention. This consisted of both Private users (n = 9) and Organisation Pool users (n=12). The pre-intervention recharging and user type of the users agreeing to take part in the intervention process, as identified in the recharging profile section of this thesis, can be seen in Figure 6-1.

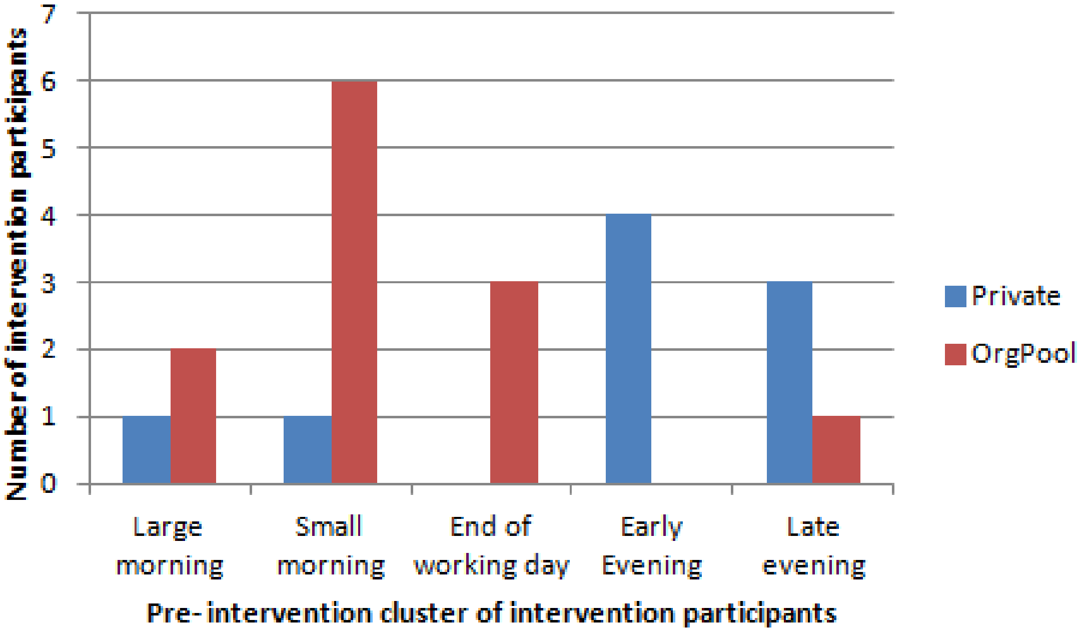

Figure 6-1: Number of intervention participants by user type and recharging profile (n= 21)

Of the Organisation Pool users, all pre-intervention recharging clusters were represented, with the exception of the users following the early evening recharging profile. The majority of pool users taking part in the interventions were the users who, pre-intervention, were in one of the two morning recharging profiles. There were two Organisation Pool users following the large morning and six users following the small morning recharging profile. Three of the Organisation Pool users followed the end of working day and one driver taking part in the interventions followed the late evening recharging profile.

This is of significant interest because Private users with access to infrastructure at home have the option of utilising the timer function to set their recharging to begin in the off peak hours. Organisation Pool users do not generally have access to at home infrastructure and recharge during the working day. As such, the results of this intervention are indicative of how infrastructure access, in terms of location, can affect the effectiveness of financial incentives as a recharging demand management tool.

No Organisation Individual users took part in the intervention process. The most frequent user type who agreed to take part in the study were the Organisation Pool users, so it would not be accurate to suggest that organisations in general were not interested in taking part.

6.3. **Selection of Control Group**

For the drivers to be considered for inclusion in the control group, they were required to have a minimum trial period that last for over 140 days (five 28 day months). This allowed their pre-intervention data and post-intervention data to be analysed in the same way as the intervention participants (taking into account road, weather and other conditions over the same period).

There were 50 Organisation Pool, 23 Organisation Individual and 11 Private users who met these criteria. This compares to 9 private and 12 Organisation Pool users in the intervention group. As there were no organisation single users taking part in the interventions, this group was not considered.

Chi-squared analysis of these data indicate that the Organisation Pool users were significantly over-represented in the group of potential control group users,

χ^2 (1) = 31.1, p = < 0.00. Therefore, nine private and 12 Organisation Pool users were required from the potential control group to avoid bias. Figure 6-2 shows the recharging profiles of the remaining potential users for the control group.

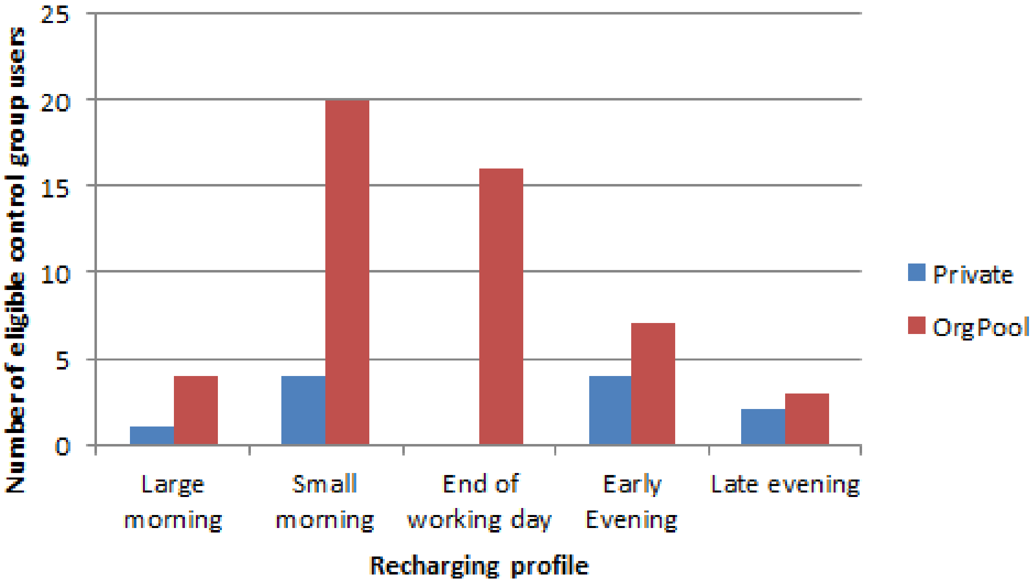

Figure 6-2: Potential control group users by user type and cluster

To ensure that the pre-intervention behaviour of the control and the intervention groups was not significantly different, drivers with a similar proportion of key characteristics were required in the two groups. The number of each user type for all combinations of pre-intervention recharging profile and home recharging access are compared to the number of potential control group users with these similar characteristics in Table 6-1.

Cluster	**User type**	**Home post?**	**Intervention user frequency**	**Potential control group frequency**
Large Morning	Private	N	1	0
	OrgPool	N	2	4
Small morning	Private	Y	1	3
	OrgPool	N	5	16
		Y	1	4
End of working day	OrgPool	N	3	16
Early evening	Private	Y	4	4
Late evening	Private	Y	3	2
	OrgPool	Y	1	2

Table 6-1: Key characteristics of intervention participants and the number of exact matches in the potential control group user pool

For Organisation Pool users taking part in the intervention, there were a minimum of two in the potential control group participants with the same home access and pre-intervention recharging profile. Therefore 12 Organisation Pool drivers were randomly selected; two from the four large morning profile, five from the sixteen small morning with no home recharging, one from the four small morning with home recharging, three from the sixteen end of working day profile and one from the two late evening recharging profile users. This means that this subset of the control group users was similar to the intervention participants in terms of these key characteristics.

All four Private users following the early evening recharging profile were selected from the potential group of control group Private users, to match the four taking part in the interventions. One of the three small morning users with home recharging access was randomly selected.

Both of the late evening profile followers were selected from the pool of potential control group users. However, there were not enough to match the three late evening recharging profiles observed in the control group. Therefore, the evening recharging profiles were under-represented by one user.

For the large morning recharging profile there was a Private user with no access to home recharging infrastructure but not in the control group. However, there was a Private user with no home recharging access following the small morning recharging profile. This user was chosen at random and allocated to the control group in place of the user in the large morning profile due to the similarity in the time of day of the recharging peak and the lack of home recharging access.

To ensure that the total number of Private users in the control group and the intervention group were similar, one of the users with home recharging infrastructure from the small morning profile was randomly selected. This is because this user type was closest in behaviour to the evening types, given the smaller, secondary peak in the evening recharging characteristics of the users following this profile. Therefore, the cluster allocation for Private user taking part in interventions and in the final control group is shown in Figure 6-3.

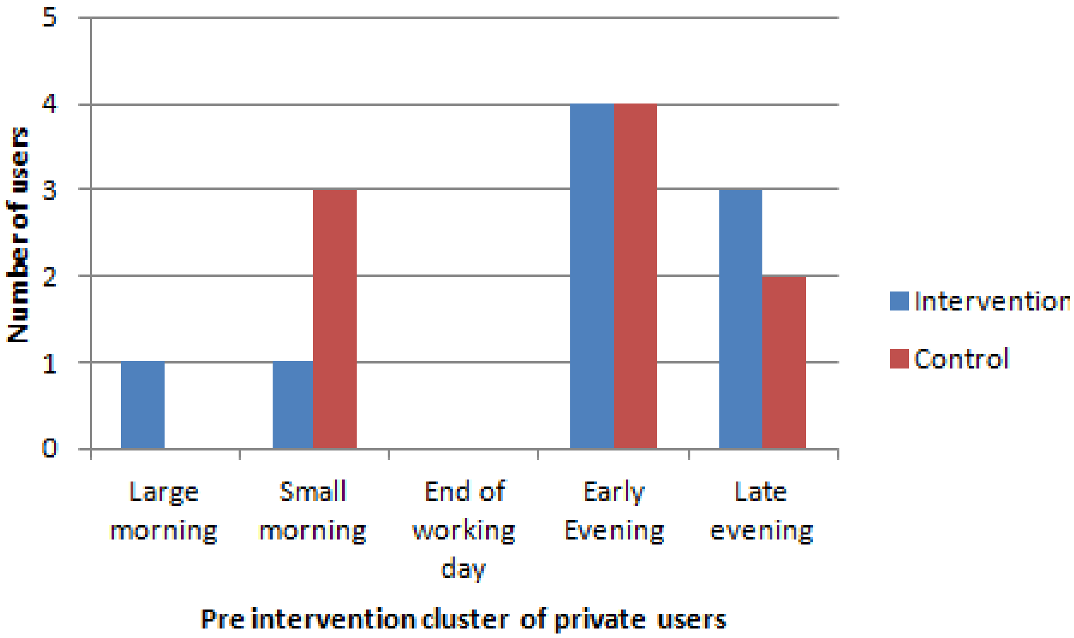

Figure 6-3: Number of Private users in the control (n=9) and intervention (n=9) groups by recharging profile

It can be seen that, for the Private users, the small morning peak was over-represented in the control group and the large morning was under-represented. It is recognised that the late evening recharging group is under-represented in the control group. The Chi squared expected cell counts when using all four profiles were below five. When cells were combined into morning and evening profiles, there were still expected cell counts below five. This means that a Chi squared test was not suitable. Therefore, a Fisher exact test was used to compare the distribution of Private users into morning and evening profiles, as shown in Table 6-2.

Private user	**Morning profiles**	**Evening profiles**
Control	3	6
Intervention	2	7

Table 6-2: Number of Private users in the control group (n= 9) and intervention group (n = 9) by peak recharging period

A Fisher exact test, based on the data from Table 3, indicated that there was no statistically significant difference in recharging demand profiles between the control and intervention groups, p = 1.00. This means that the Private users in the control group can be considered as representative of the users taking part in the intervention scheme.

Therefore, the intervention group and the control group can be considered to have displayed the same pre-intervention recharging behaviour. The number of users in the control group, in terms of user type, recharging behaviour and access to home recharging infrastructure, was not significantly different. As such, differences in behaviour between the intervention participants and the control group can be considered due to the intervention.

6.4. Control Group Analysis

6.4.1. Overall Percentage Difference in Off-Peak Recharging before and after the Intervention Period

This section investigates changes in recharging behaviour in the control group as a whole. This was to determine whether there were any changes occurring throughout the trial that was not intervention related. The overall percentage point change was the measure proposed in this research to explore the success of the intervention and was defined in Chapter 3.

The overall percentage point change in hours of off-peak recharging before and after the 78 day intervention period was used to determine whether there were any differences in behaviour of the control group before and after the interventions.

The percentage point changes in off-peak was shown to be statistically significantly different from normal, as indicated by a Shapiro-Wilk test ($p<0.05$). Figure 6-4 illustrates the distribution of percentage point changes in off-peak recharging before and after the 78 day intervention period for the control group.

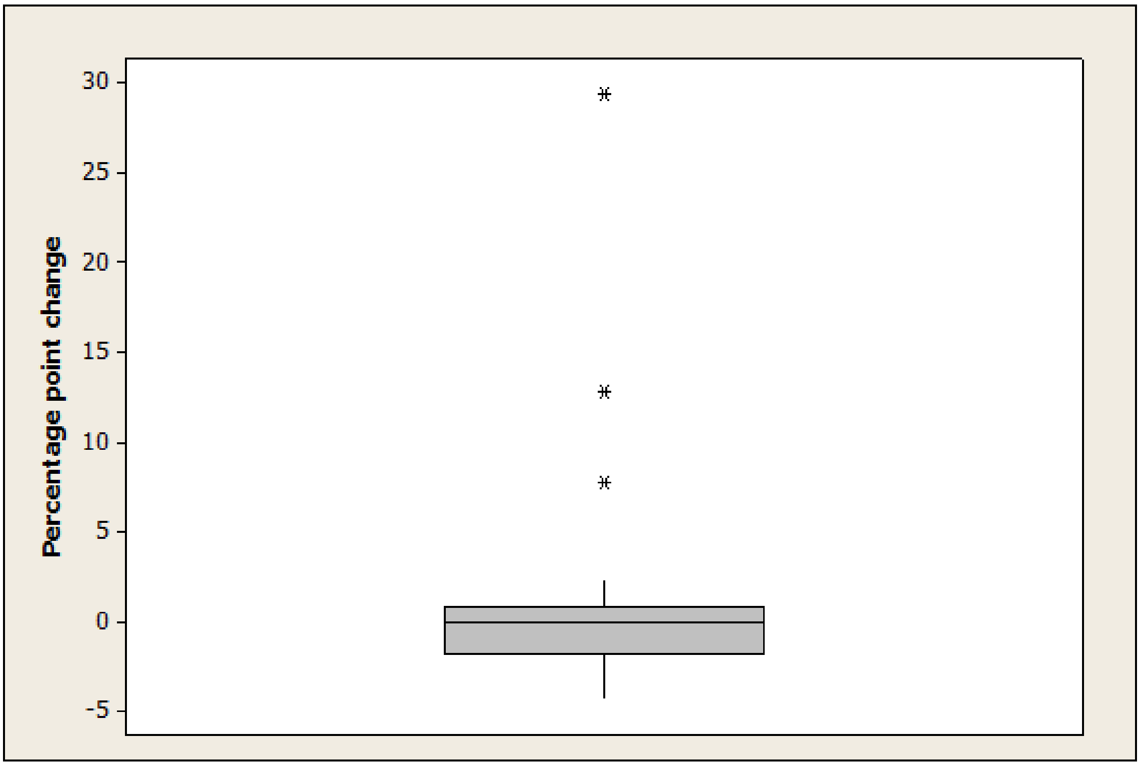

Figure 6-4: Percentage point change in the relative proportion of off-peak recharging (n = 21) at all locations

The lower quartile was -1.8%, the upper quartile was 0.8% and the median was 0.0%. A Wilcoxon Signed Rank test indicates that this median was not significantly different from zero (p = 0.94). This provides evidence that there was not a statistically significant change in the proportion of time spent recharging during the off-peak hours for the control group, taking into account all locations.

This finding is important because it can be assumed that any changes in the percentage of time spent recharging off-peak in the post-intervention time period for the group of intervention participants was due to the intervention rather than any external factors.

The change in the percentage of recharging taking place off-peak before and after the intervention by location was tested. A Shapiro-Wilk test indicated that all five recharging locations were not normally distributed (p<0.05). Figure 6-5 illustrates the difference in the percentage of off-peak recharging, by location, for all users in the control group. The quartile values for these distributions can be seen in Table 6-3. The results of a Wilcoxon Signed Rank test, for the median percentage point change differing significantly from zero, for each location, can be seen in Table 6-4.

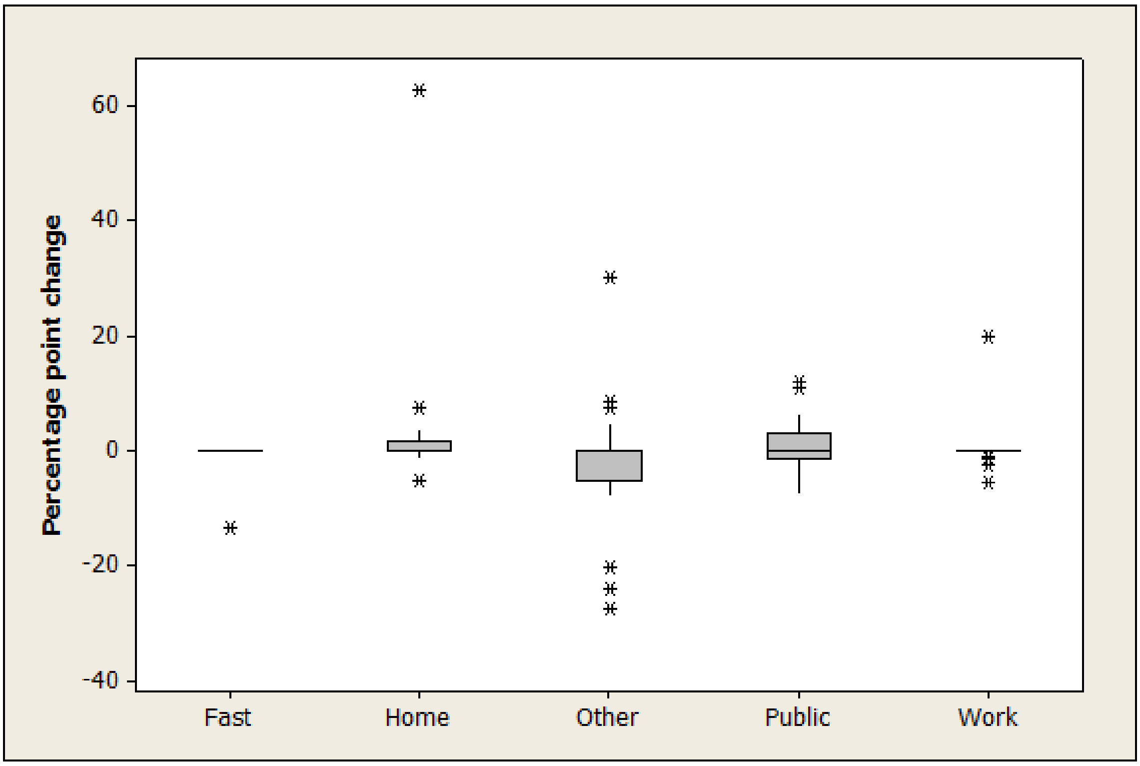

Figure 6-5: Percentage point change in the relative proportion of off-peak recharging (n = 21) by location

Location	Lower Quartile	Median	Upper Quartile
Fast	0.0	0.0	0.0
Home	0.0	0.0	1.0
Work	0.0	0.0	0.0
Public	-0.7	0.0	1.8
Other	-4.3	0.0	0.0

Table 6-3: Quartile values of the percentage point change in the relative proportion of off-peak recharging (n = 21) by location

Location	p-value (median vs zero)
Fast	0.32
Home	0.98
Work	0.76
Public	0.56
Other	0.44

Table 6-4: Wilcoxon Signed Rank test results for median percentage point change in the relative proportion of hours of off-peak by location (n = 21)

The median values were all zero. Considered alongside the p-value results from the Wilcoxon Signed Rank tests, it can be concluded that there was no evidence of any behavioural shift in recharging behaviour at any of the locations for the users in the control group (p>0.05 for all locations). This was expected, as there have been no incentives offered that could influence recharging behaviour. However, this also confirms that there were no other influences that would cause drivers to change recharging behaviour mid-trial.

This builds on the finding from the analysis of the overall recharging data and is important because any changes in the proportion of recharging occurring during the off-peak hours for the intervention participants, at any location, can be attributed to the intervention alone.

It is recognised that not all users had access to home and work recharging infrastructure. Therefore, this analysis was repeated for the home and work recharging locations, only considering users who made use of recharging infrastructure at these locations. This removed any zero values that occurred due to a driver not having made use of recharging at these locations. There were 10 users of home recharging infrastructure and 11 users for work recharging infrastructure. The Shapiro-Wilk test indicated that neither was normally distributed ($p < 0.00$). The percentage point changes for home are illustrated in Figure 6-6 and for users of work recharging infrastructure in Figure 6-7.

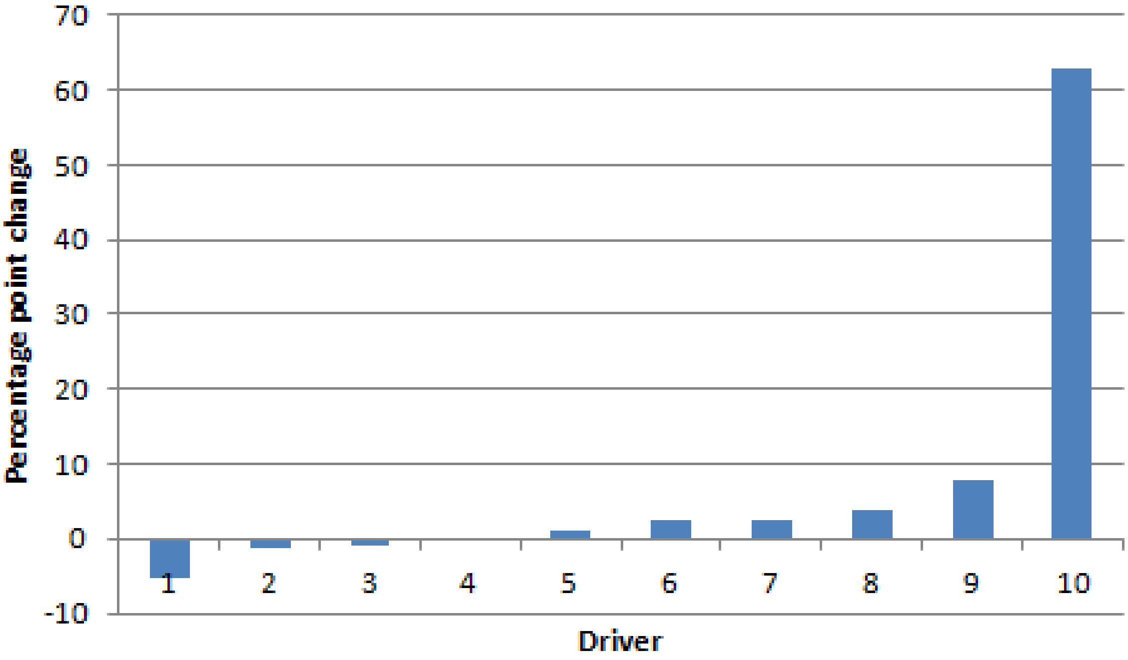

Figure 6-6: Percentage point change in total hours of off-peak recharging for users of home (n = 10)

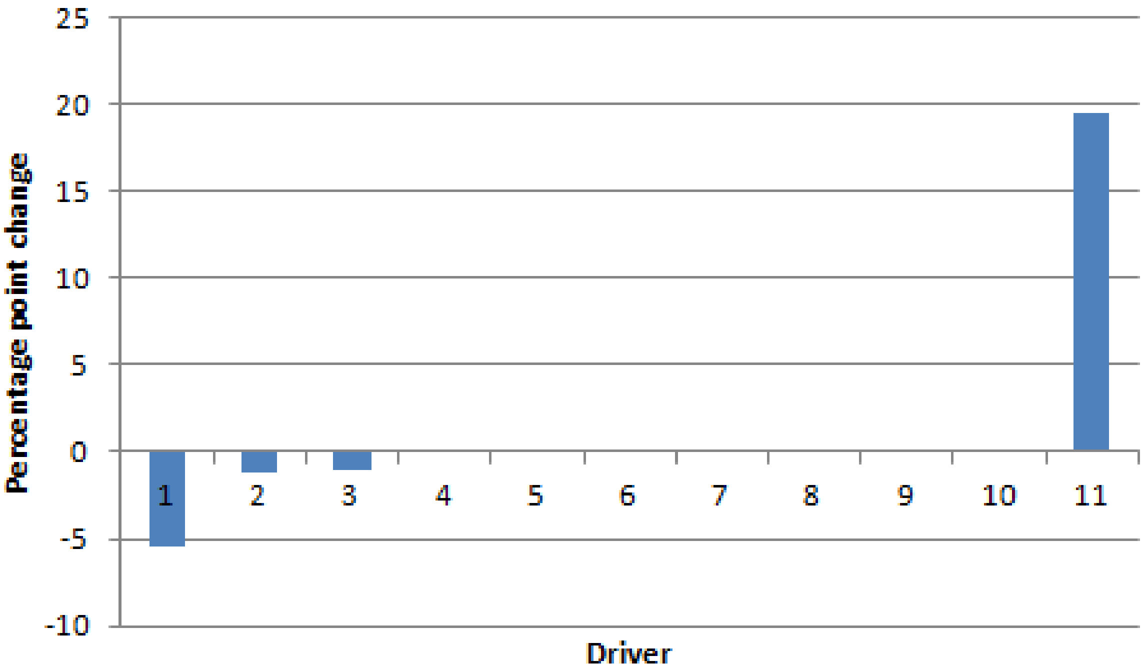

Figure 6-7: Percentage point change in total hours of off-peak recharging for users of work recharging infrastructure (n = 11)

The lower quartile was -0.6% at home and -0.5% at work. The median was 1.7% at home and 0.0% at work. The upper quartile was 3.6% at home and 0.0% at work. The Wilcoxon Signed Rank test indicates that the median of both distributions was not significantly different from zero (p = 0.17 for home and p = 0.72 for work).

In terms of the outliers, there was a vehicle with a recorded increase in off-peak recharging frequency of 62.8%. There was a different vehicle with an increase of 19.2% in off- peak recharging. Both of these vehicles were organisation pool vehicles, with multiple users. Some of these users had recharging at home and some did not. These differences are thought to be due to different drivers having access to the vehicles throughout the trial period, with the respective differences in recharging behaviour, due in part to where these users have access to recharging, being reflected in the results.

The significance of this is that the proportion of off-peak recharging overall did not differ depending on whether or not a control group user had access to recharging infrastructure at home or work locations. Furthermore, the results of the previous analysis for the proportion of off-peak recharging by members of the control group of users were not influenced in any statistically significant way by whether or not the users had access to either home or work recharging infrastructure.

6.4.2. Difference between Recharging Infrastructure Usage before and after the Intervention Period

This section explores the changes in the relative amount of recharging, in terms of total number of hours, between the pre-intervention and post-intervention data for users in the control group. The percentage point differences in relative hours spent recharging between the pre and post intervention period were not normal for all five locations. This was indicated by Shapiro-Wilk tests (p < 0.00 in all cases).

The distribution of the percentage point change between the relative usages of recharging infrastructure for all locations can be seen in Figure 6-8. Table 6-5 illustrates the quartile values of these distributions, and Table 6-6 presents the results of Wilcoxon Signed Rank tests to determine whether the median percentage point change was significantly different from zero at each location.

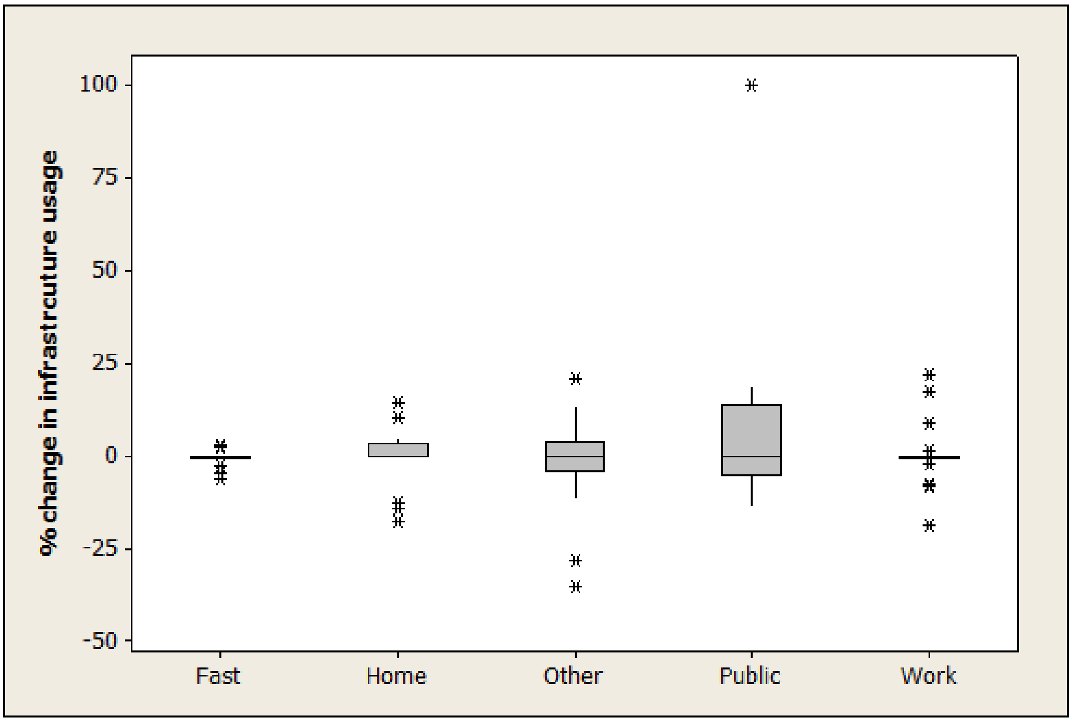

Figure 6-8: Percentage point changes in recharging infrastructure usage post intervention for all users in the control group at all locations (n = 21)

Location	Lower Quartile	Median	Upper Quartile
Fast	-0.7	0.0	0.0
Home	0.0	0.0	3.5
Other	-4.2	0.0	3.8
Public	-5.1	0.0	13.8
Work	-0.6	0.0	0.0

Table 6-5: Control group quartile values of the percentage point change in the relative usage of recharging infrastructure post intervention (n = 21)

Location	p-value (median vs zero)
Fast	0.11
Home	0.80
Other	0.92
Public	0.53
Work	0.96

Table 6-6: Wilcoxon Signed Rank test result for the change in the proportion of recharging hours post intervention (n = 21 per location)

It can be seen that the median values were again all zero, with no statistically significant difference between the pre-intervention and post-intervention data. This indicates that users in the control group did not change the proportion of their recharging time at each location before and after the interventions took place.

As such, when analysing changes in the control group, any differences in the proportion of recharging at any of the recharging locations are attributable to the intervention process alone.

Due to the fact that not all users had access to home recharging, and some users did not make use of any workplace recharging either before or after the intervention, this analysis was repeated for home and work locations, using only users who had made use of these locations before the interventions took place. This was to ensure that median percentage point changes of zero did not occur due to users not having made use of infrastructure at these locations due to access restrictions.

Results from Shapiro-Wilk tests (critical p-value of 0.05) indicate that the change in percentage points between pre and post intervention for home recharging were normally distributed (p=0.12). The distribution was also normally distributed at work (p = 0.61). Figure 6-9 shows the percentage point change for users of home recharging infrastructure, at home locations. The distribution for users of work recharging infrastructure at work only is illustrated in Figure 6-10.

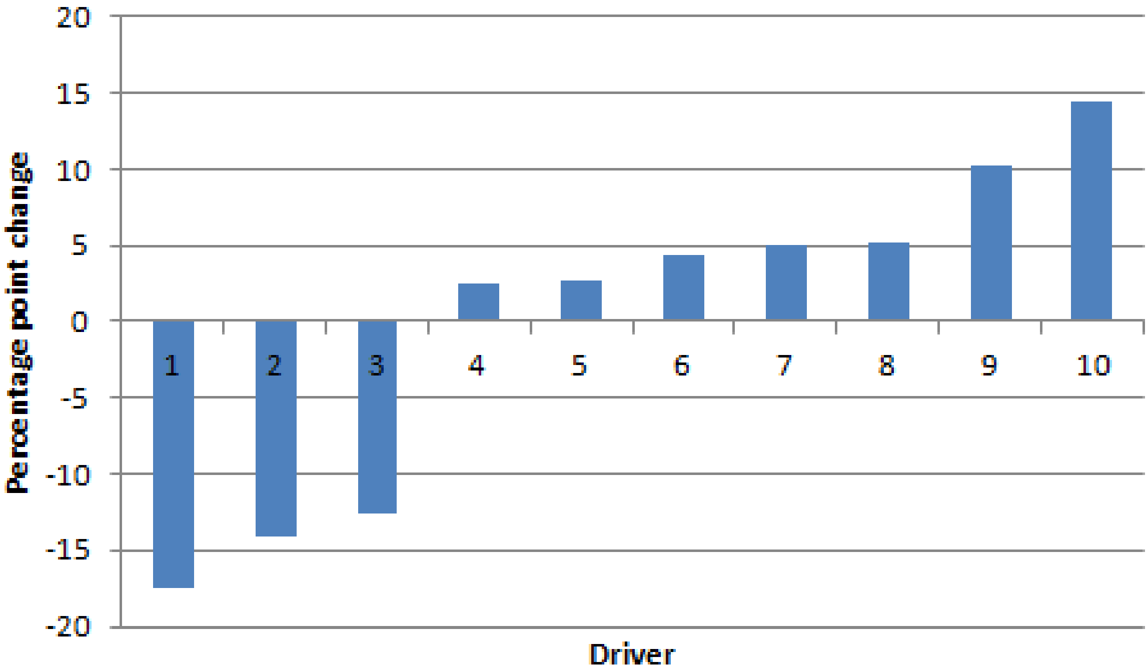

Figure 6-9: Percentage point change in recharging infrastructure usage post intervention period at home, for home users only (n = 10)

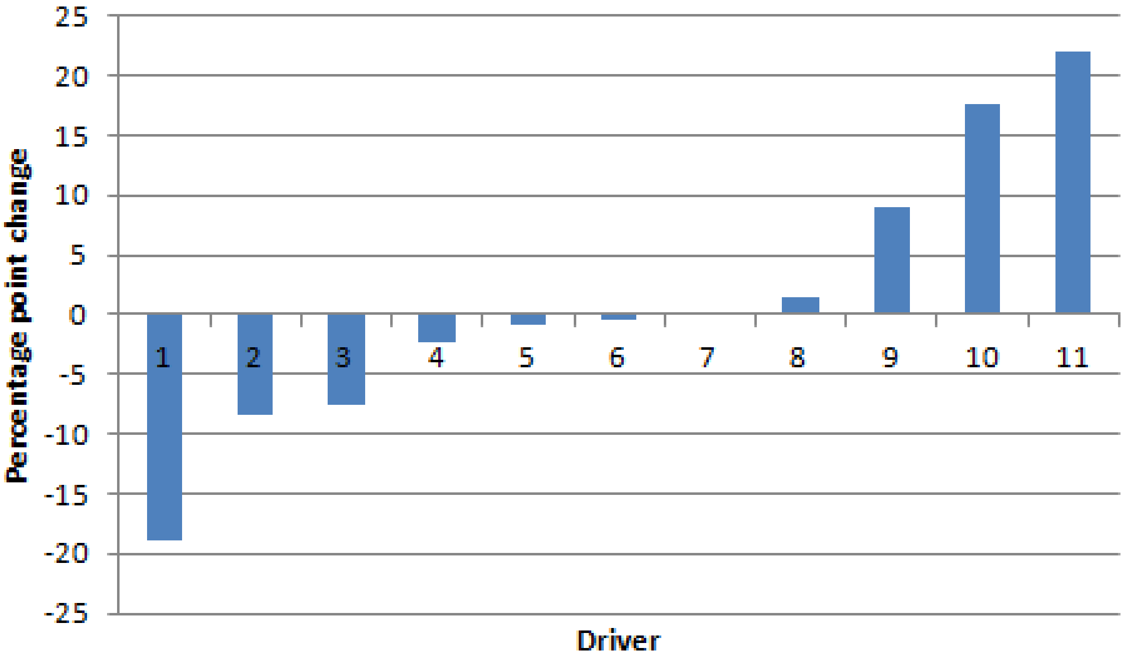

Figure 6-10: Percentage point change in recharging infrastructure usage post intervention period at work, for work users only (n = 11)

The lower quartiles for these distributions were -8.8% for home and -4.9% for work. The medians were 3.5% for home and -0.5% for work. The upper quartiles were 5.1% for home and 5.3% for work.

The t-test results indicate that the mean (standard deviation) value of 0.1% (±10.9%) at home for the distribution of percentage point differences between the recharging completed at home before and after the intervention period was not significantly different from zero (95% CI,-7.7% to 7.8%), t (9) = 0.01, p = 0.99. At work, the mean value of 1.1% (±11.6%) was not significantly different from zero (95% CI,-6.7% to 8.9%), t (10) = 0.31, p = 0.76.

These statistics indicate that, for the users of home and work recharging infrastructure in the control group, there was no change in the relative usage of these locations, in terms of the proportion of hours of recharging, before and after the intervention period. This confirms that the previous test for all users at this stage was not influenced by the fact that some users did not use the recharging infrastructure at these locations either before or after the event.

In summary, it can be seen that there was no evidence of a change in the usage of recharging infrastructure between the pre-intervention and post-intervention period, in terms of relative number of hours of recharging recorded at each location. Therefore, when assessing the impact of the interventions, it can be assumed that any statistically significant change in usage of recharging infrastructure for the intervention participants, at any location, was due to the intervention rather than any other external factors.

6.4.3. Difference in Off-Peak Recharging by Post-Intervention Month

One of the aims of this analysis is to understand whether the intervention is likely to offer a temporary, or longer last change (if any change) in behaviour. Therefore, it is important to know whether the control group changed their behaviour on a temporary basis in any of the months during their equivalent post-intervention period.

The Sharipo-Wilk test indicates that the distribution of percentage point changes for all three post intervention months was not normal (p<0.00). Figure 6-11 illustrates the percentage point change in off-peak recharging before and after the 78 day intervention period for the selected control group during the three post intervention months.

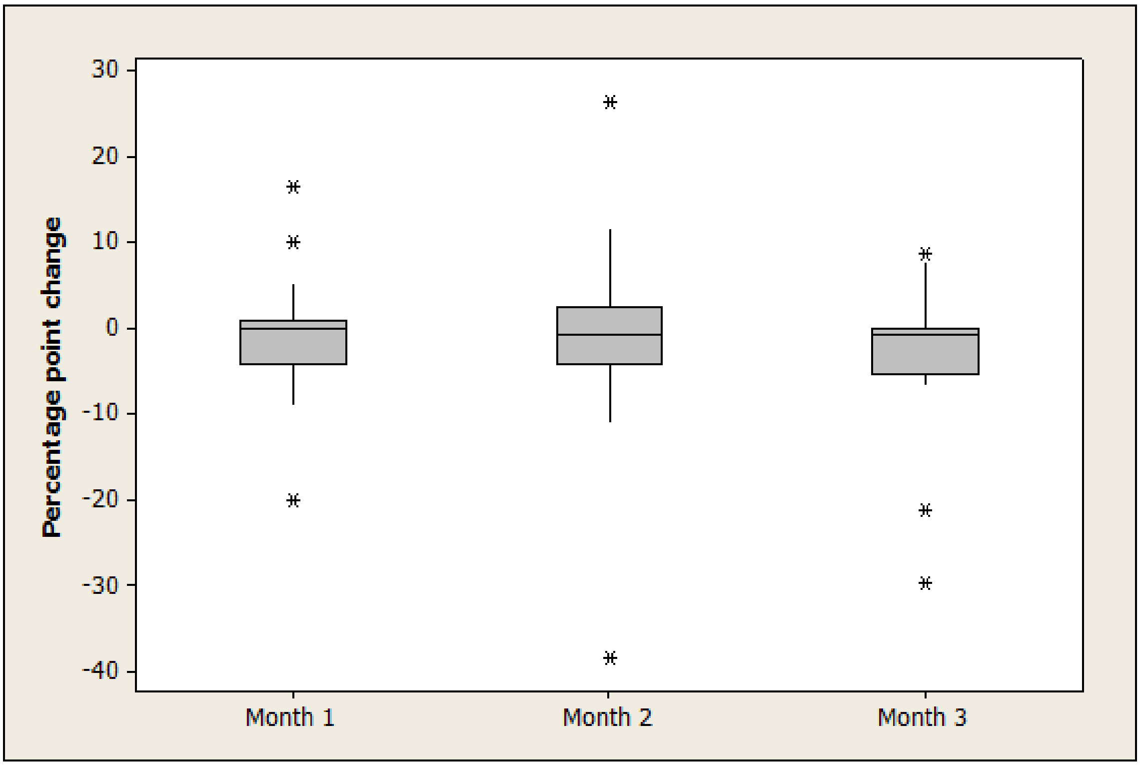

Figure 6-11: Percentage point change in total hours of off-peak recharging before and after the intervention period (n = 21)

For month 1, the lower quartile was-4.2%, the median was 0.0% and the upper quartile was 1.1%. A Wilcoxon Signed Rank Test indicates that this was not significantly different from zero (p=0.38). For month 2, the lower quartile was-4.1%, the median was 0.7% and the upper quartile was 2.6%. This median was not significantly different from zero (p=0.52). For month 3, the lower quartile was-5.2%, the median was-0.8% and the upper quartile was 0.0%. The median value for month 3 was not significantly different from zero (p=0.13).

This knowledge can be used to interpret the results of the intervention group behaviour on a month by month basis. For intervention participants, any significant changes in the proportion of recharging taking place during the off-peak hours can be attributed to the intervention. This is because there is no evidence that the control group changed the proportion of off-peak recharging during their equivalent post-intervention time period.

6.4.4. Quantifying the Differences in Control Group Carbon Content of Electricity during EV Recharging during Pre and Post-Intervention Time Periods

This section explores whether the average carbon content of electricity per recharging event for each control group user changed significantly. Both winter and summer recharging profiles were applied to all recharging events recorded by users in the recharging profiles.

When the winter carbon content of electricity profiles were applied to all recharging events recorded by the control group, there was no recharging in the 350 ≥ gCO_2/kWh > 400 or 400 ≥ gCO_2/kWh > 450 ranges. This was due to the minimum average carbon content being greater than these values at all times of the day.

The Shapiro-Wilk test indicates that the 450 ≥ gCO_2/kWh > 500 bracket was not normally distributed ($p = 0.00$). However, the 500 ≥ gCO_2/kWh > 550 bracket was normally distributed ($p = 0.42$), as was the 550 ≥ gCO_2/kWh > 600 bracket was normally distributed ($p = 0.51$). The quartile values for these distributions can be seen in Table 6-7.

Carbon content (gCO_2/kWh)	**Lower Quartile**	**Median**	**Upper Quartile**
>= 350 and < 400	-	-	-
>=400 and < 450	-	-	-
>= 450 and < 500	-1.7	-0.4	0.0
>= 500 and < 550	-3.7	3.2	7.0
>= 550 and < 600	-6.4	0.3	6.8

Table 6-7: Control group percentage point change in the carbon content of electricity per recharging event post intervention using the winter CO_2 profile

The distribution of the difference in percentage points for the proportion of recharging events with carbon contents within each observed range when the winter carbon content profile is applied can be seen in Figure 6-12.

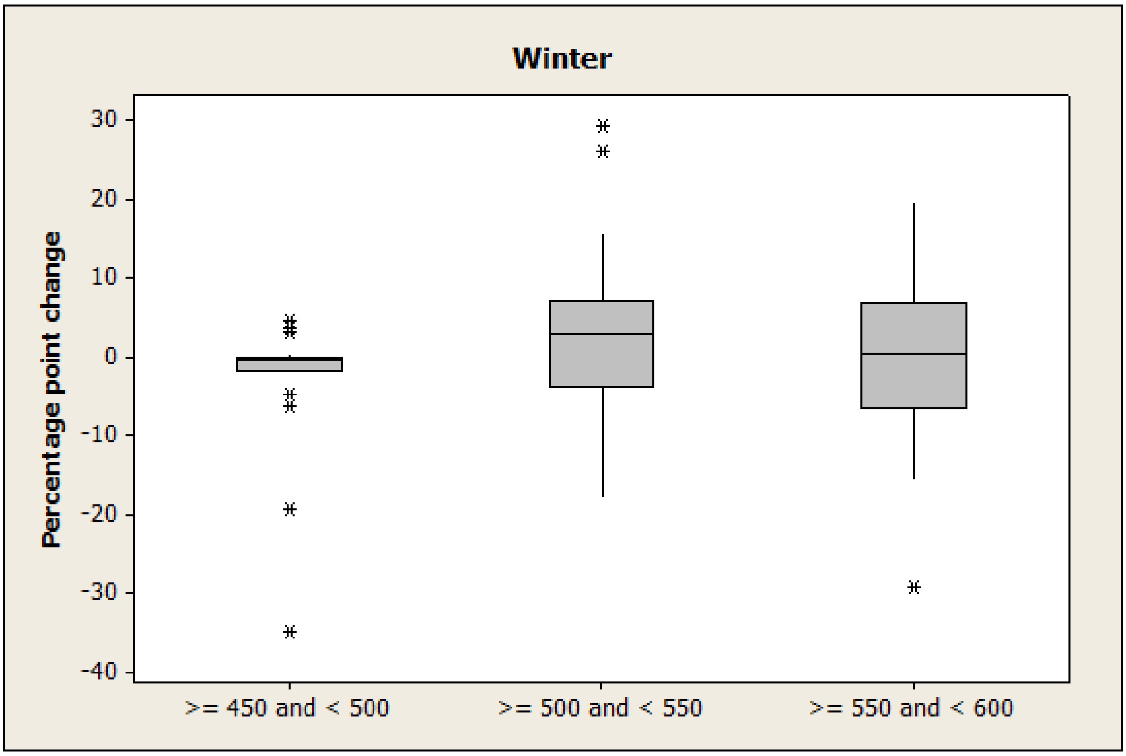

Figure 6-12: *Percentage point change in the carbon content of electricity during EV recharging post intervention using the winter CO_2 profile (n = 21)*

A Wilcoxon Signed Rank test indicates that the median proportion of recharging events in the 450 ≥ gCO_2/kWh > 500 bracket did not differ significantly from zero (p = 0.11).

A t-test indicates that the mean value of 2.9% (±8.7%) for the 500 ≥ gCO_2/kWh > 550 bracket was not significantly different from zero (95% CI,-6.9% to 1.1%), t (20) =-1.51, p = 0.15. For the 550 ≥ gCO_2/kWh > 600 bracket, the mean of 3.6% (±11.3%) was not significantly different from zero, (95% CI,-1.5% to 8.7%), t (20) = 1.47, p = 0.16.

This illustrates that there was no change in the carbon content of electricity of EV recharging when winter carbon contents were applied to the recharging events of users in the control group. Given that there was no change in the percentage of off-peak recharging behaviour, it was not expected that there would be a significant change in the carbon content of recharging of the control group.

In summer, there were no recharging events with a carbon content in the 550 ≥ gCO_2/kWh > 600 bracket. This was because the maximum average daily carbon content in summer was less than 550gCO_2/kWh.

The Shapiro-Wilk test indicates that the 350 ≥ gCO_2/kWh > 400 and the 400 ≥ gCO_2/kWh > 450 bracket were not normally distributed (p = 0.00). The 450 ≥ gCO_2/kWh > 500 bracket was normally distributed (p = 0.89), as was the500 ≥ gCO_2/kWh > 550 bracket (p = 0.74). Table 6-8 illustrates the quartile values of these percentage point change distributions.

Carbon content (gCO_2/kWh)	**Lower Quartile**	**Median**	**Upper Quartile**
>= 350 and < 400	0.0	0.0	0.0
>=400 and < 450	-2.4	0.0	3.2
>= 450 and < 500	-2.1	0.9	8.0
>= 500 and < 550	-1.4	0.0	5.2
>= 550 and < 600	-	-	-

Table 6-8: Percentage point change in the carbon content of electricity per recharging event post intervention using the summer CO_2 profile

The change in carbon content when the summer carbon content of electricity profile was applied to recharging events in the control group can be seen in Figure 6-13.

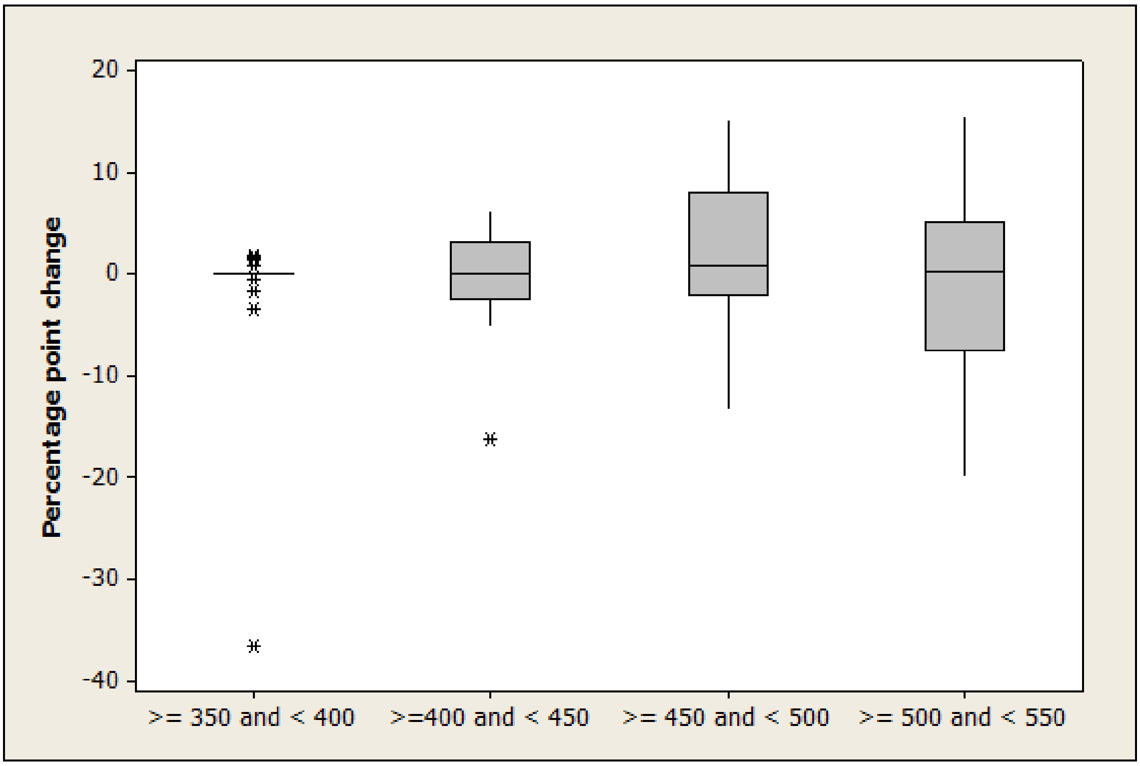

Figure 6-13: Percentage point change in the carbon content of electricity during EV recharging post intervention using the winter CO_2 profile (n = 21)

The Wilcoxon Signed Rank test indicates that the 350 ≥ gCO_2/kWh > 400 bracket was not significantly different from zero (p = 0.77). The 400 ≥

$gCO_2/kWh > 450$ bracket was also not significantly different from zero ($p = 0.76$). The t-test outputs indicate that the mean value of 2.2% (±7.3%) for the $450 \geq gCO_2/kWh > 500$ bracket was not significantly different from zero (95% CI,-1.1% to 5.5%), t (20) = 1.38, p = 0.18. The mean value of-0.2% (±9.1%) for the $500 \geq gCO_2/kWh > 550$ bracket was not significantly different from zero (95% CI,-4.4% to 3.9%), t (20) =-0.12, p = 0.90. Again, due to the lack of a change in the proportion of recharging taking place during the off-peak hours, this result was expected.

Overall the analysis confirms that there was no significant change in the carbon content of electricity, before and after the intervention process, for users in the control group. This was true for both the summer and winter recharging profiles. From this it can be inferred than any statistically significant post-intervention change in the carbon content of electricity for the intervention users can be considered to be due to changes in recharging behaviour as a result of the interventions.

6.4.5. Impact of Control Group Results on Intervention Analysis

There were no statistically significant changes observed in the control group of users before and after the intervention process. No changes were observed in terms of the proportion of hours spent recharging off-peak and subsequently no changes were observed in the carbon content of electricity used to recharge the EVs. There was also no significant change in the number of recharging events at each location.

Therefore, there is no requirement for any correction factors applied to the post-intervention results of the intervention participants and that any statistically significant changes in off-peak recharging, at any location, and the subsequent changes in carbon content of electricity, can be considered to be accredited to the intervention process.

6.5. Intervention Participant Results

6.5.1. Overall Changes in Frequency of Off-Peak Recharging

A Shapiro-Wilk test indicated that the distribution of the differences in the percentage of off-peak recharging, before and after the intervention, were not normally distributed ($p < 0.00$).

The lower quartile of the difference in percentage points between the pre and post intervention aggregated off-peak recharging times was-1.2%, the median was 2.3% and the upper quartile was 10.6%. The Wilcoxon Signed Rank test indicates that this median value was statistically significantly different from zero ($p = 0.30$). This suggests that, on the whole, the intervention process had a statistically significant impact on the recharging behaviour of EV drivers.

This is a key finding of this research and indicates that financial incentives can be used to influence driver recharging behaviour. Although the change in behaviour overall was statistically significant, the result was not large enough to shift the majority of recharging hours into the off-peak. The conclusion to draw from this analysis is that, although financial incentives were found to be statistically significantly effective, they cannot be used as a standalone tool to manage recharging without additional measures being taken. The following sections of this thesis presents the results of the analysis of the impact of financial incentives in more detail in order to further understand their role in managing recharging demand.

6.5.2. Changes in Frequency of Off-Peak Recharging by Location

This section investigates the changes in the relative number of hours of off-peak recharging that took place at each of the recharging locations, before and after the interventions, for all recharging events recorded by each of the intervention participants. The Shapiro-Wilk test indicates that the distribution of the change in off-peak recharging before and after the interventions was not normal ($p < 0.00$) for all locations except public ($p = 0.49$). These changes can be seen in Figure 6-14.

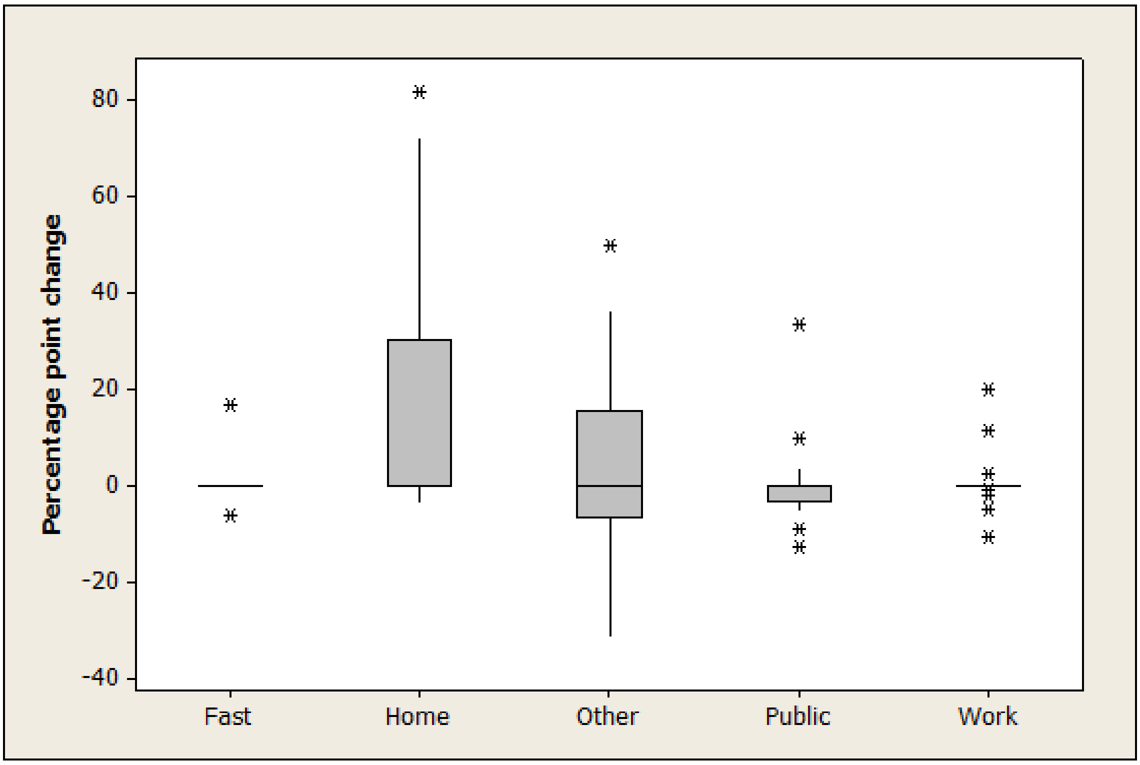

Figure 6-14: Percentage point change in off-peak recharging frequency post intervention by location (n = 21)

The quartile values of these distributions can be seen in Table 6-9.

Location	Lower Quartile	Median	Upper Quartile
Fast	0.0	0.0	0.0
Home	0.0	1.1	30.1
Other	-6.5	0.0	15.7
Public	-3.1	0.0	0.2
Work	0.0	0.0	0.0

Table 6-9: Quartile values of the overall percentage point change in off-peak recharging post intervention by location (n = 21)

Wilcoxon Signed Rank tests indicated that the median values did not differ significantly from zero for fast (p = 0.67), other (p = 0.44), or work (p = 0.74). The median was significantly different from zero at home (p = 0.01). A t-test indicated that the mean value of 0.3% (±9.2%) for public recharging did not differ from zero (95% CI,-16.7% to 1.2%), t (21) = 0.17, p = 0.87.

The median at home was found to be statistically significantly different from zero when using the Wilcoxon Signed Rank test. As the lower quartile was zero, this indicates that there was a majority of drivers who did not make a notable change to their recharging habits at home. However, there was a subset of intervention participants whose increase in off-peak recharging post-intervention was sufficient to significantly shift the centrality measure of the distribution as a whole. This is indicated by the upper quartile percentage point change of 30.1% at home.

The lower quartile and median values were exactly zero for percentage point change. These zero values corresponded to users who did not have access to home recharging infrastructure. Therefore, this result was not due to home recharging habits remaining the same. Instead, this result can be explained by the fact that they did not recharge at home at all, either before or after the intervention. The percentage point change in off-peak recharging at home was therefore zero before and after the intervention. Hence, the percentage point change in off-peak recharging was also zero.

The high upper quartile value for recharging at home suggests that there was a specific group of users who changed their recharging behaviour at home. To prove this and to quantify changes in home recharging behaviour for drivers with access, this analysis was then repeated using data for all users who made use of some home and work recharging during the trials (n = 9 at home and n = 12 at work).

The Shapiro-Wilk test indicates that home was normally distributed (p = 0.34) and work was not normally distributed (p = 0.01). The percentage point changes in off-peak recharging can be seen in Figure 6-15 for home users off-peak recharging at home and in Figure 6-16 for work users recharging at work.

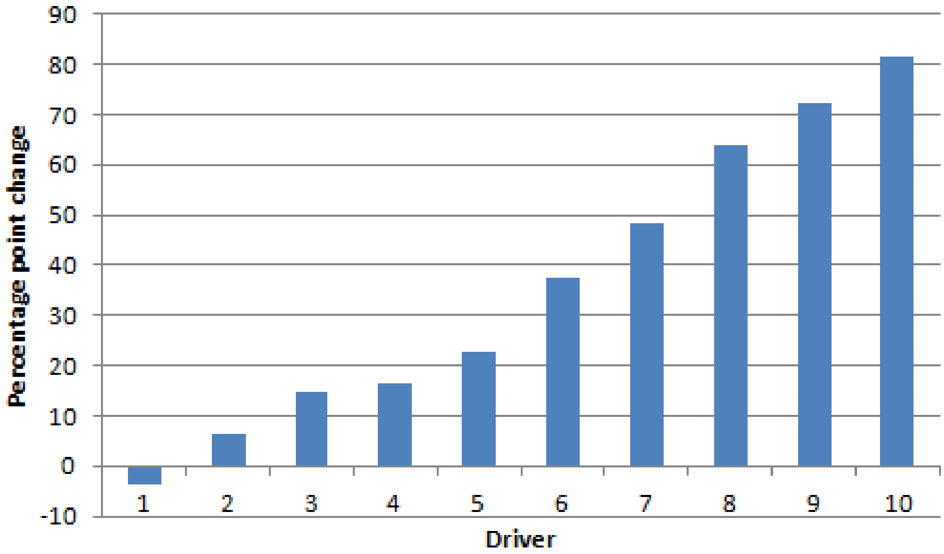

Figure 6-15: Percentage point change in recharging infrastructure usage post intervention for users of home recharging infrastructure (n = 10)

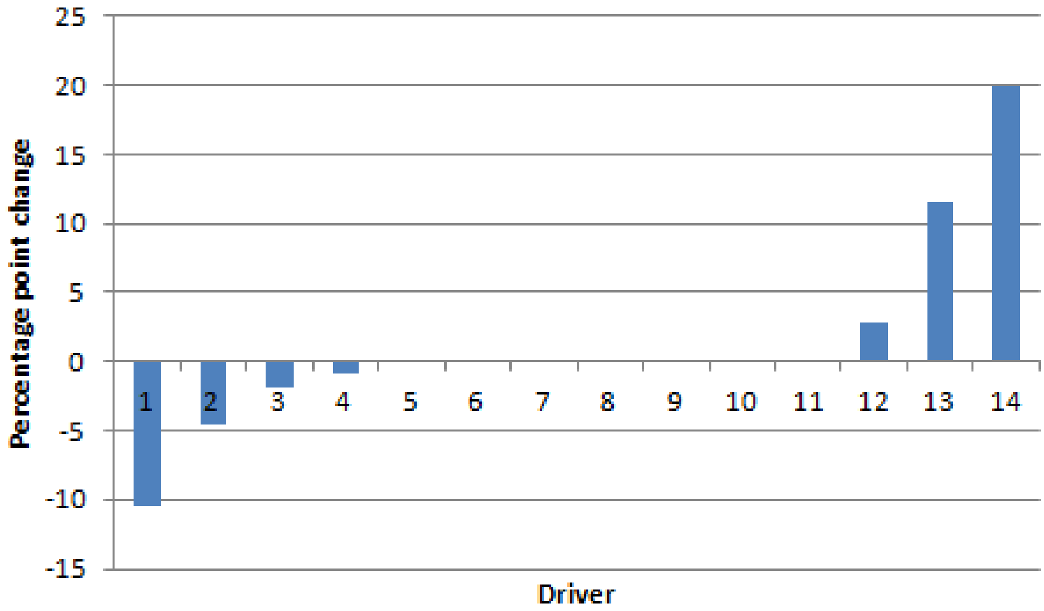

Figure 6-16: Percentage point change in recharging infrastructure usage post intervention for users of work recharging infrastructure (n = 14)

The quartiles (lower, median, upper) were; Home (6.2%, 22.7%, 63.9%) and work (-1.4%, 0.0%, 0.0%). A Wilcoxon Signed Rank test indicated that the median was not statistically significantly different from zero for recharging at work (p = 0.01). The T-test result proved that, for home recharging, the mean value of 32.7 (±30.0) was statistically significantly different from zero (95% CI, 12.6% to 52.9%), t (10) = 3.61, p = 0.01.

Of the five users home users recording the largest percentage increase in total frequency of recharging, four were private users. This highlights the relative ease at which private vehicle users can modify their recharging routine compared to organisation pool users. The two users recording the greatest increase at work was a private user. This user did not change the percentage of their total recharging taking place at work (12.3% pre-intervention vs 11.9% post-intervention). Therefore, this was due to this driver having access to a work recharging post and changing the way in which it is used. This would occur when the vehicle was being parked at work overnight. This result provides some evidence that organisation pool vehicle rules regarding plugging in the vehicle on return to base can limit the effectiveness of financial incentives as a recharging demand management tool.

A key finding of this research is that the intervention influenced behaviour at home, with a median increase of 22.7% in off-peak recharging. This proves that the values observed when recharging at home for all users were due to a lack of home recharging infrastructure access. The role of smart meter access at home, when combined with the offer of a financial incentive, is validated by this finding and should be encouraged by policy makers.

However, the intervention did not lead to a significant increase in off-peak recharging for users with access to dedicated workplace recharging posts. Focus group discussion reveals that this was likely due to a combination of a lack of timing devices making it impractical to recharge off-peak at work and company policy requiring all EVs to be plugged in to recharge immediately on return to base to be ready for the next utilisation of the vehicle.

6.5.3. Analysis of Changes in Frequency of Recharging Infrastructure Usage for Users taking part in Interventions

This section investigates whether the total amount of recharging at each of the locations, in terms of total duration, shifted for the users taking part in the interventions between the pre and post-intervention periods.

The Shapiro-Wilk test shows that the percentage point change in relative usage of recharging infrastructure at fast recharging posts was normal ($p = 0.96$), home was not normal ($p = 0.04$), other was not normal ($p = 0.04$), public was normal ($p = 0.09$) and work was not normal ($p < 0.00$). These distributions are illustrated in Figure 6-17. The quartile values for these distributions can be seen in Table 6-10.

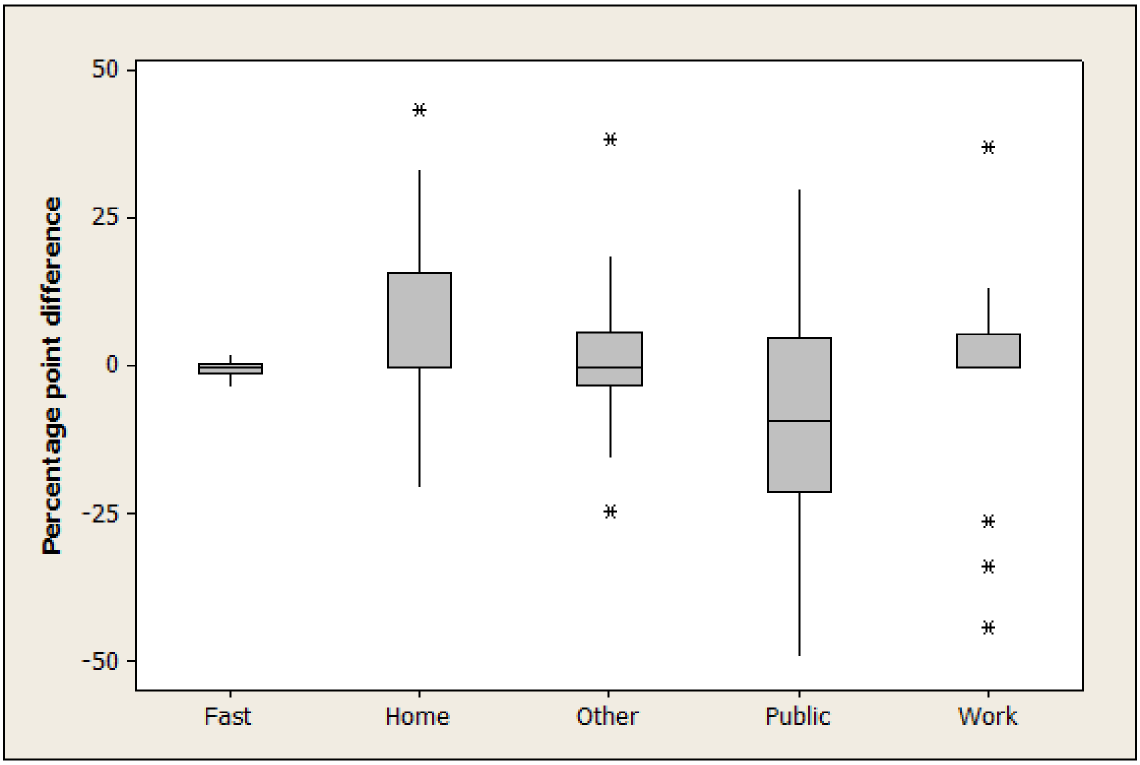

Figure 6-17: Percentage point change in frequency of infrastructure usage before and after the intervention (n = 21)

Location	Lower Quartile	Median	Upper Quartile
Fast	-1.7	0.0	0.7
Home	0.0	0.0	11.1
Other	-2.4	3.4	6.3
Public	-18.1	-12.1	3.6
Work	0.0	0.3	5.6

Table 6-10: Quartile values for percentage point change in frequency of infrastructure usage post intervention (n = 21)

The Wilcoxon Signed Rank tests indicated that the medians were not significantly different from zero at home (p = 0.06), other (p = 0.47) and work (p = 0.39) recharging locations. For fast recharging infrastructure, the mean percentage point change in usage between the pre and post intervention period of-1.4% (±1.4%) was not significantly different from zero (95% CI,-0.8% to 0.5%), t (20) =-0.5, p = 0.66. At public recharging locations, the mean of-7.8% (±1.4%) was not significantly different from zero (95% CI,-16.7% to 1.2%), t (20) =-1.8, p = 0.09.

It can therefore be concluded that, for the intervention group of users as a whole, there was no statistically significant change in the relative usage of recharging infrastructure at each of the locations. However, it is recognised that not all users had an option to recharge at home.

The significance of this finding is that, although financial incentives and smart meters were effective in influencing recharging behaviour into the off-peak hours at home, there was no shift in the proportion of recharging taking place at each location. As indicated by SwitchEV participants in the focus groups, this is likely to be due to the convenience of non-domestic parking spaces in city centre locations and the perceived free parking disincentivising users from transitioning to more home-focused recharging.

When considering data only from those users with pre-intervention recharging recorded at home (n = 11), Shapiro-Wilk tests indicate that both distributions of the percentage point changes in relative usage at these locations were normally distributed for fast (p = 0.75), home (p = 0.98), other (p = 0.56) and public (0.90). Work was not normally distributed (p = 0.01). The quartile values of these distributions can be seen in Table 6-11.

Location	Lower Quartile	Median	Upper Quartile
Fast	-1.8	0.0	7.4
Home	-0.9	11.1	29.7
Other	-2.4	2.6	3.7
Public	-26.9	-18.1	3.0
Work	0.0	0.0	2.7

Table 6-11: Quartile values for percentage point change in recharging infrastructure usage post intervention at home (n = 11)

T-test outputs indicate that the mean at fast locations was-0.5% (±1.4%), which was not significantly different from zero (95% CI,-1.6% to 0.7%), t (10) =-0.91, p = 0.39. The mean at home was 12.3% (±19.6%). This was not significantly different from zero (95% CI,-0.9% to 25.5%), t (10) = 2.08, p = 0.06. The mean at other locations was 1.9% (±8.9%). This was not significantly different from zero (95% CI,-4.1% to 7.8%), t (10) = 0.70, p = 0.50.

At public locations, the mean value of-14.9% (±8.9%) did not differ significantly from zero (95%CI,-29.7% to-0.1%), t (10) =-2.24, p = 0.05. The Wilcoxon Signed Rank test indicates that the median value of 0.0% at work was not significantly different from zero (p = 0.35).

This is important because it proves that, even for users with a recharging post at home, the incentive scheme did not encourage an increase in home based recharging rather than the non-domestic recharging locations.

Shapiro-Wilk tests were conducted on the distribution of the percentage point difference in infrastructure usage, pre and post intervention, for all locations for users of work recharging infrastructure (n = 15). These were normally distributed at fast recharging locations (p = 0.25), other (p = 0.42), public (p = 0.81) and work (p = 0.07). The home data did not follow a normal distribution (p = 0.01). The percentage point changes are illustrated in Figure 6-18, and the quartile values of these distributions are presented in Table 6-12.

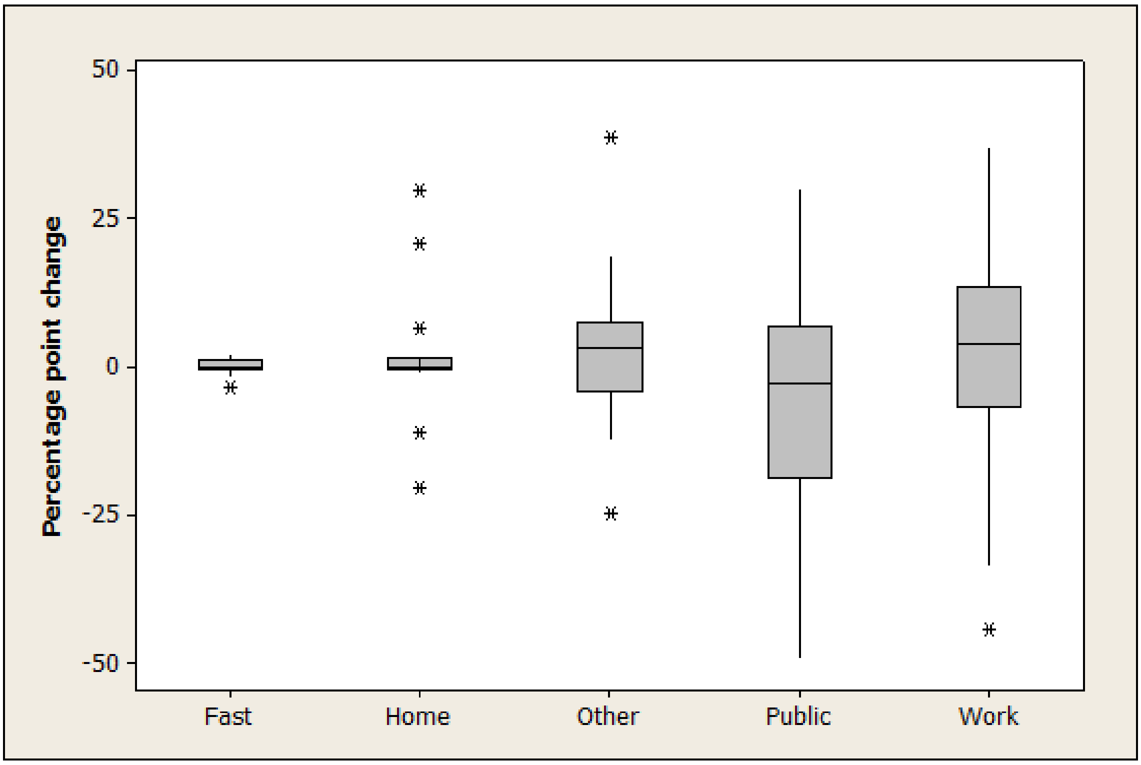

Figure 6-18: Percentage change in recharging infrastructure usage post intervention period for users of work recharging infrastructure (n = 15)

Location	Lower Quartile	Median	Upper Quartile
Fast	-0.4	0.0	1.2
Home	-0.2	0.0	1.7
Other	-4.1	3.1	7.7
Public	-18.5	-2.7	7.0
Work	-6.8	4.0	13.5

Table 6-12: Quartile values for percentage point change in recharging infrastructure usage post intervention at work (n = 15)

The changes in the normally distributed locations were analysed using t-tests. The mean at fast locations was 0.1% (±1.5%), which was not significantly different from zero (95% CI,-0.8% to 9.0%), t (14) = 0.16, p = 0.87. At other locations, the mean was 3.3% (±14.6%). This was not significantly different from zero (95% CI,-5.2% to 11.7%), t (14) = 0.83, p = 0.42. At public locations, the mean value of-4.7% (±21.2%) was not significantly different from zero (95% CI,-17.0% to 5.7%), t (11) =-0.83, p = 0.42. At work, the mean value was-0.4% (±21.1%). This was not significantly different from zero (95% CI,-12.6% to 11.8%), t (14) =-0.07, p = 0.94. A Wilcoxon Signed Rank test indicates that the distribution of percentage changes in the frequency of home recharging usage pre and post intervention were not significantly different from zero (p = 0.60).

This suggests that, of the users with access to work recharging, there was no change in where recharging takes place at once the interventions had taken place.

The significance of this is that there was no evidence to suggest that recharging locations could be influenced by offering financial incentives aimed to encourage off-peak recharging to drivers in this region. As discussed in focus groups, incentives to purchase EVs in the North East of England, with the annual membership fee for public infrastructure, have created an environment in which drivers recharge at public locations, even when it is not required.

Therefore, it can be suggested that if recharging is to be effectively managed, there must be a change in the access mechanism for EV recharging infrastructure, such that drivers are not incentivised to recharge on-peak. There is a role for smart meters to play in managing demand at recharging locations. However, from this analysis, it has become apparent that smart meters, as a standalone tool installed at home, are not effective in managing a shift away from public and workplace locations during the day.

Provision of smart meters at home as a recharging demand tool is a key component of the OLEV strategy for managing recharging demand. This strategy is reliant on EVs being parked at home, which is not the case for Organisation Pool vehicles. A key limitation revealed in the current trials was a lack of timing devices provided for use in non-domestic recharging infrastructure. By providing smart meters for use in the workplace, recharging could be better managed. Also there is a need for policy to ensure that, where possible, fleet vehicles are not plugged in and recharged immediately upon returning to the workplace when the vehicle has no further business that day.

6.5.4. Analysis of Month by Month Changes in Off-Peak Recharging Behaviour

There were up to three months of data collected from vehicles during the post-intervention period. Four drivers did not lease the vehicle into a third post-intervention month. Therefore, the sample sizes were 21, 21 and 17 for months 1, 2 and 3 respectively.

Sharipo-Wilk tests indicate that the distribution of the differences in percentage points for off-peak relative to peak recharging, before and after the intervention process was normal for month 1 ($p = 0.69$) and for month 3 ($p = 0.10$), but not for month 2 ($p < 0.00$). The distributions are visualised in Figure 6-19 and the quartile values of these distributions are illustrated in Table 6-13.

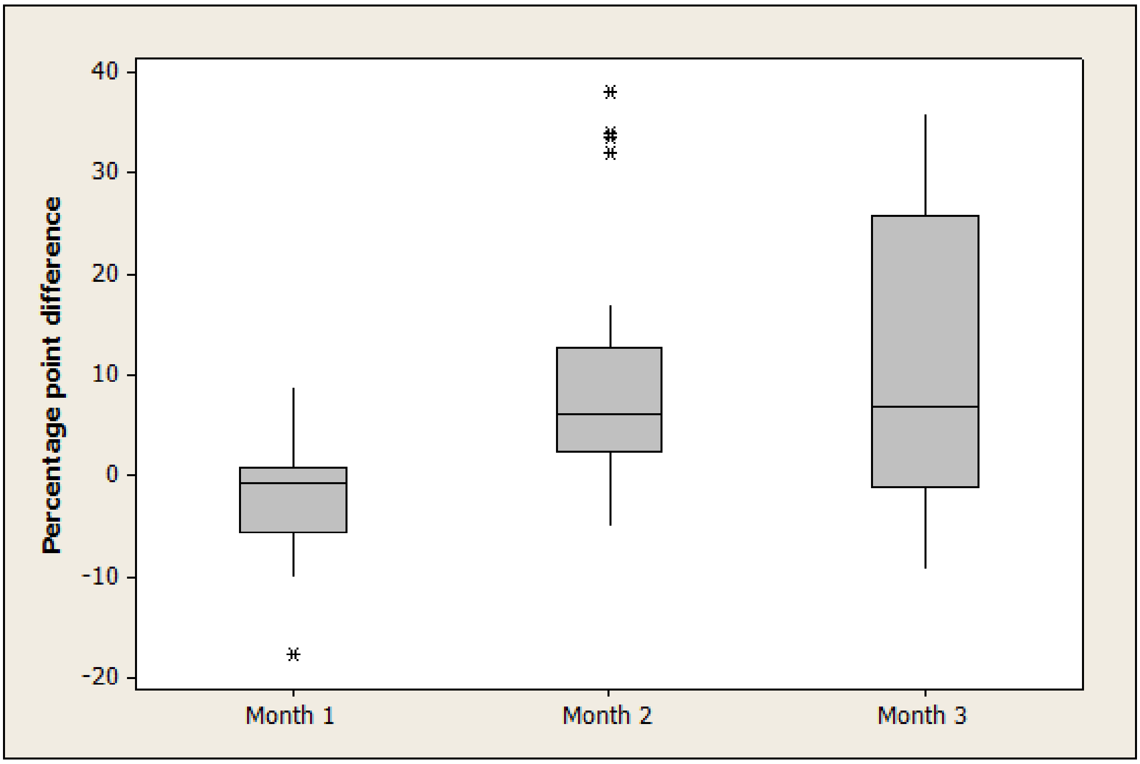

Figure 6-19: Percentage point change in off-peak recharging post intervention for all users by post-intervention month (n = 21)

Months post-intervention	**Lower Quartile**	**Median**	**Upper Quartile**
1	-7.6	0.7	2.1
2	-0.3	3.1	24.5
3	1.1	6.9	25.8

Table 6-13: Quartile values for percentage point change in off-peak recharging post intervention for all users by post-intervention month (n = 21)

A t-test indicates that mean percentage point change of-1.9% (±6.2%) was not significantly different from zero for month 1 (95% CI,-4.8% to 1.9%), t (20) =-1.42, p = 0.17. A Wilcoxon Signed Rank test indicates that the median value for month 2 was not significantly different from zero ($p < 0.00$). A t-test indicated that the mean value of 10.2 (±13.4%) was significantly different from zero (95% CI, 3.3% to 17.1%), t (16) = 3.1, p = 0.01.

This indicates that the effect of the intervention was not immediate. Drivers typically took one month to significantly increase the amount of recharging undertaken in the off-peak hours. This could be due to initial distrust of the timing devices.

The implication for policy over the longer term is that there was no evidence of drivers immediately abandoning the habit of off-peak recharging once it was adopted. It is speculated that this habit would be maintained beyond three months, but further research would be required to validate this prediction.

6.5.5. Carbon Content of Electricity during EV Recharging for Intervention Participants

The impact of this behavioural change of the carbon content of electricity during EV recharging is now explored. Using winter profiles, there were no data for the $350 \geq gCO_2/kWh > 400$ or the $400 \geq gCO_2/kWh > 450$ bracket due to the minimum carbon content being greater than 450. Shapiro-Wilk tests indicate that the $450 \geq gCO_2/kWh > 500$ bracket was not normally distributed (p = 0.04). The distribution of the $500 \geq gCO_2/kWh > 550$ bracket was normal (p = 0.63), as was the $550 \geq gCO_2/kWh > 600$ bracket (p = 0.44).

The distribution of the percentage point change in the number of recharging events in each of the three winter brackets can be seen in Figure 6-20. The quartile values of these distributions are presented in Table 6-14.

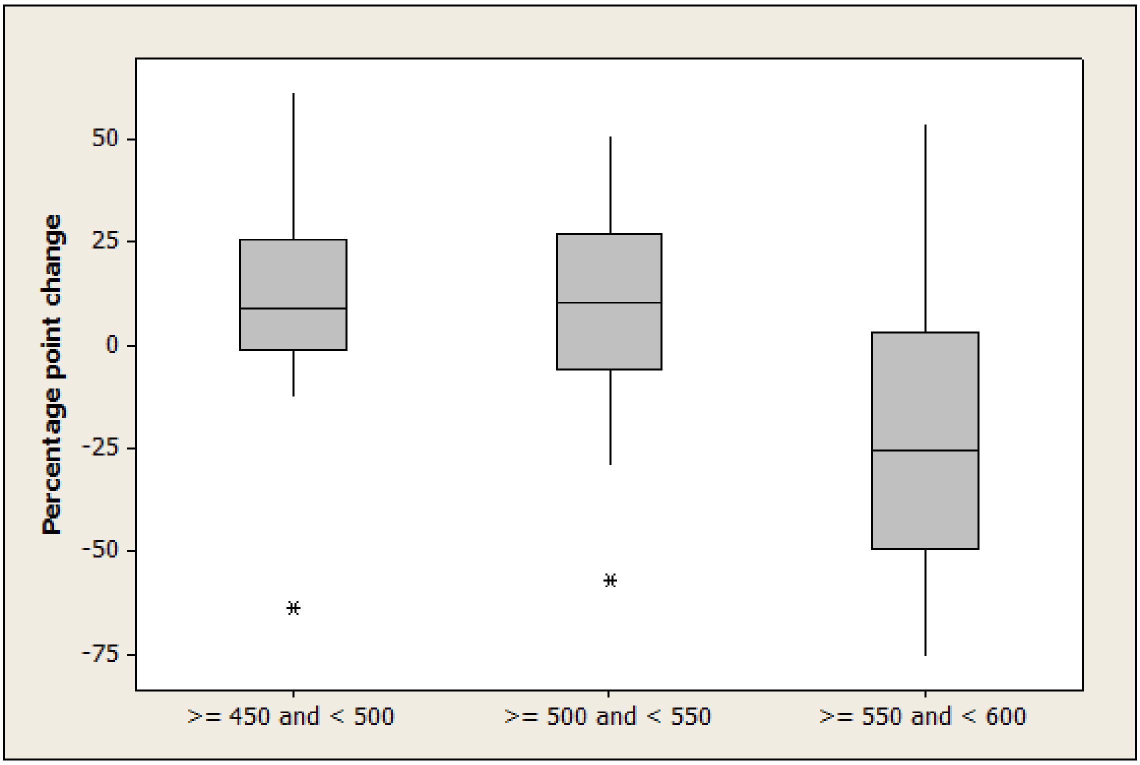

Figure 6-20: Percentage point change in carbon content of electricity during EV recharging post-intervention using the winter carbon content profile (n = 21)

Carbon content (gCO_2/kWh)	**Lower Quartile**	**Median**	**Upper Quartile**
>= 350 and < 400	-	-	-
>=400 and < 450	-	-	-
>= 450 and < 500	-1.1	8.9	25.6
>= 500 and < 550	-5.9	10.2	27.0
>= 550 and < 600	-49.3	-25.7	3.1

Table 6-14: Quartile values for percentage point change in carbon content post-intervention using the winter carbon content profile (n = 21)

The Wilcoxon Signed Rank test indicated that the median of the 450 ≥ gCO_2/kWh > 500 bracket was significantly different from zero (p = 0.01). The t-test results indicate that the mean value of 9.4% (±27.2%) for the 500 ≥ gCO_2/kWh > 550 bracket was not significantly different from zero (95% CI,-3.0% to 27.1%), t (20) = 1.58, p = 0.13. A t-test indicated that the mean value of-20.5% (±34.9%) for the 550 ≥ gCO_2/kWh > 600 bracket was significantly different from zero (95% CI,-36.4% to-4.6%), t (20) =-2.69, p = 0.01.

This provides evidence that a proportion of the recharging events with high carbon content took place during times of day where the carbon content was lower once the intervention had taken place.

When applying the summer carbon content of electricity profile to recharging events, there was no recharging with a carbon content in the 550 ≥ gCO_2/kWh > 600 bracket. The Shapiro-Wilk test indicates that the 350 ≥ gCO_2/kWh > 400 bracket and the 400 ≥ gCO_2/kWh > 450 bracket were not normally distributed ($p = 0.00$). The 450 ≥ gCO_2/kWh > 500 bracket was normal ($p = 0.24$), as was the 500 ≥ gCO_2/kWh > 550 bracket ($p = 0.74$).

The percentage point change in the number of recharging events taking place within each of the carbon content brackets when the summer profile was applied to the pre-intervention and post-intervention recharging events are presented in Figure 6-21. The quartile values of these distributions can be seen in Table 6-15.

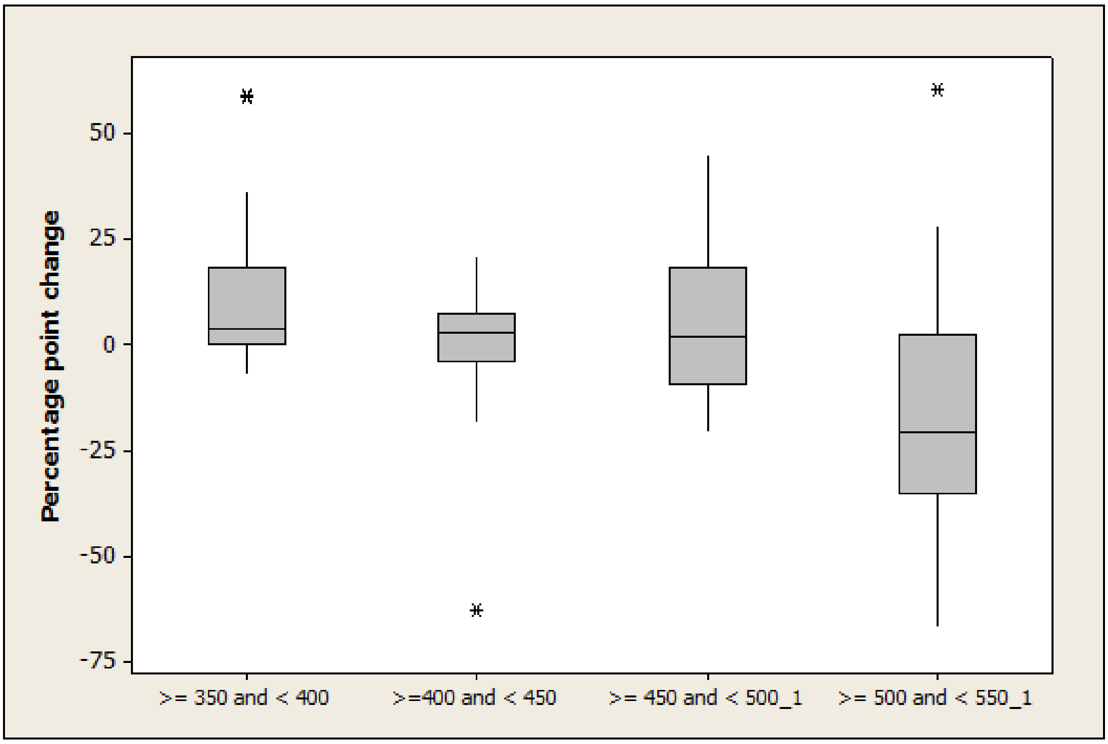

Figure 6-21: Percentage point change in the carbon content of electricity during EV recharging post-intervention using the winter carbon content profile (n = 21)

Carbon content (gCO_2/kWh)	**Lower Quartile**	**Median**	**Upper Quartile**
>= 350 and < 400	0.2	4.0	18.3
>=400 and < 450	-3.9	2.8	7.8
>= 450 and < 500	-9.1	2.3	18.5
>= 500 and < 550	-35.0	-20.4	2.8
>= 550 and < 600	-	-	-

Table 6-15: Quartile values for percentage point change in carbon content of EV recharging post intervention using the summer carbon content profile (n = 21)

The Wilcoxon Signed Rank test indicates that the 350 ≥ gCO_2/kWh > 400 bracket was significantly different from zero (p = 0.00). The 400 ≥ gCO_2/kWh > 450 bracket did not differ significantly from zero (p = 0.50). A t-test shows that the mean value of 5.3% (±16.8%) for the 450 ≥ gCO_2/kWh > 500 bracket was not significantly different from zero (95% CI,-2.4% to 13.0%), t (20) = 1.44, p = 0.17. The mean for the 500 ≥ gCO_2/kWh > 550 bracket was-16.6% (±30.8%). This was significantly different from zero (95% CI,-30.7% to-2.6%), t (20) = 2.47, p = 0.02. As observed in the winter profile, a significant number of recharging events with high carbon content did not occur with the same relative frequently post intervention.

Overall, there was a significant shift in the carbon content of electricity during EV recharging. The move into the off-peak hours lowered the number of recharging in the highest carbon content values in both summer and winter and shifted it into the lowest brackets. This was expected due to the increase in off-peak recharging behaviour overall.

6.5.6. Further Analysis of Home Recharging Behaviour for Drivers Participating in Intervention Scheme

Given that the only significant impact of the intervention scheme was to encourage a shift in recharging times of day at home, this change is investigated more closely in this section. To analyse the times of day, data were collated into four time periods; off-peak (≥00:00h and <06:00h), morning (≥06:00h and < 12:00h), afternoon (≥12:00h and <18:00h) and evening (≥18:00h and <24:00h).Shapiro-Wilk tests indicate that the distribution of percentage changes before and after the off-peak were normally distributed for off-peak (p = 0.22), afternoon (p = 0.30) and evening (p = 0.84). Morning was not normal (p = 0.00). The mean, median and quartile values of these distributions are quoted in Table 6-16.

Period of day	Lower Quartile	Median	Upper Quartile
Off-peak	0.0	14.6	48.4
Morning	-7.7	-0.7	0.0
Afternoon	-14.3	-7.6	0.5
Evening	-55.6	-26.3	-4.8

Table 6-16: Quartile values for percentage point change in frequency of recharging by the period of day for home recharging post intervention (n = 11)

The t-test results indicate that the mean value of 24.5% (±27.3%) for the off-peak period was significantly different from zero (95% CI, 6.1% to 41.8%), t (10) = 2.98, p = 0.01. This indicates a significant increase in off-peak recharging at home. The mean value for afternoon was -5.7% (±15.9%). This was not significantly different from zero (95% CI,-16.4% to 4.9%), t (10) =-1.20, p = 0.26. For evening recharging, the mean value was -27.3% (±33.1%). This was significantly different from zero (95% CI,-49.5% to-5.1%), t (10) =-2.74, p = 0.02. The Wilcoxon Signed Rank test indicates the median value of-0.7% for morning recharging was significantly different from zero (p = 0.03).

This illustrates that recharging was reduced in the morning and evening periods, by-0.7 and-27.3 percentage points respectively. Both of these changes were statistically significant. Drivers did not change the proportion of recharging taking place at home during an afternoon. This is expected as SwitchEV drivers were employed full time, so EVs are not likely to be parked at home on afternoons.

More research is needed to quantify the extent to which off-peak recharging at work could be achieved if workplace recharging was fitted with similar reprogrammable recharging devices and companies were offered incentives to utilise this functionality.

Overall, the key shift in recharging demand that was facilitated by the intervention process was the reduction in evening recharging and the subsequent increase in recharging during the off-peak hours. The proportion of recharging that was recorded during the off-peak period increased by an average of 24.5 percentage points over all intervention participants. The overall proportion of recharging in each of these four time periods, post-intervention, can be seen in Table 6-17.

Period of day	Lower quartile	Median	Upper quartile	Mean
Off-peak	11.4	38.1	69.8	41.2
Morning	0.0	0.9	7.4	5.0
Afternoon	0.0	10.5	17.4	15.2
Evening	7.1	18.0	25.0	20.4

Table 6-17: Percentage of total recharging taking place by time of day post intervention for users of home recharging infrastructure (n = 11)

With reference to the data presented in Table 6-17 the off and evening peak were normally distributed, which was not the case for the morning and afternoon peak.

Shapiro-Wilk tests indicate that the percentage of total hours of recharging post-intervention were normally distributed for the off-peak ($p = 0.11$) and evening ($p = 0.16$) periods. They were not normal for morning ($p = 0.00$) and afternoon ($p = 0.00$). Overall, the mean was 41.9% (±32.1%) for off-peak home recharging and 20.4% (±19.0%) for evening home recharging. The median was 0.9% for morning recharging and 10.5% for afternoon recharging.

It can be concluded that the intervention scheme was successful in encouraging drivers to shift some of their recharging into the off-peak hours at home. Given that the median proportion of recharging taking place off-peak was less than 50%, it can be concluded that the majority of off-peak recharging at home still took place during the on-peak hours.

6.5.7. Impact of Total Recharging Duration on Intervention Success

The total duration of post-intervention hours of recharging recorded are compared to the percentage point change in off-peak recharging behaviour in this section. This was to determine whether the intervention was dependent on the total amount of recharging undertaken by a user. The total post-intervention number of hours and the corresponding percentage point change increase in off-peak recharging behaviour can be seen in Figure 6-22.

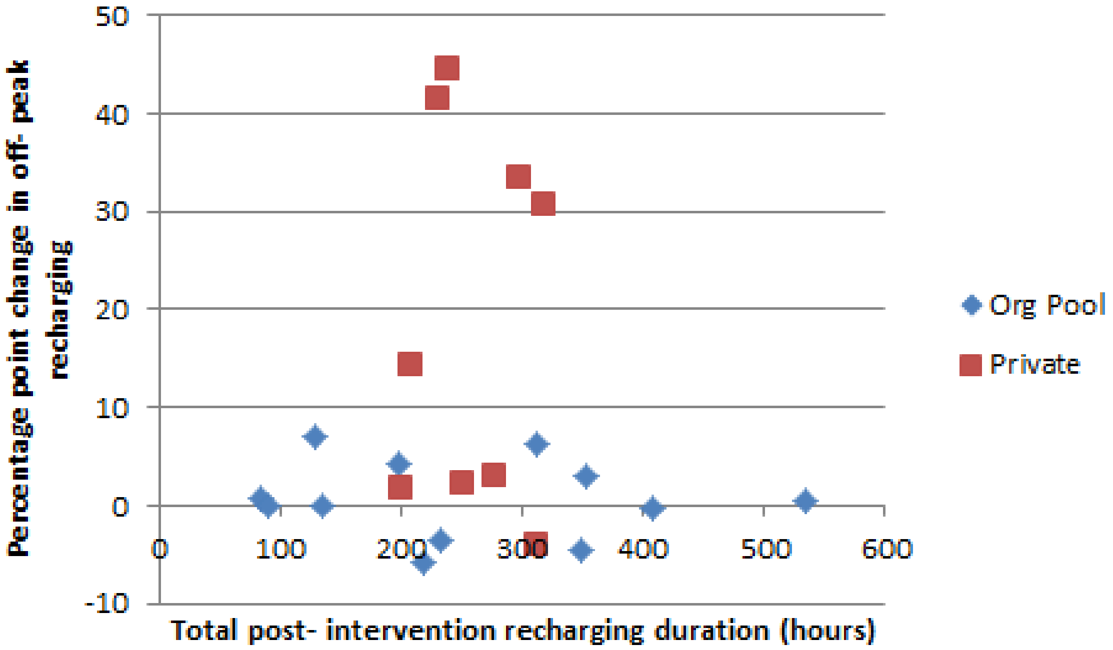

Figure 6-22: Comparison between total hours of recharging and percentage point change in off-peak recharging behaviour (n=21)

For all intervention participants the correlation coefficient-0.004 (p = 0.98). For the Organisation Pool users, the correlation coefficient was-0.09 (p = 0.76). The correlation coefficient for Private users was-0.01 (p = 0.98).

Therefore, for both user types, the result suggests that there was no evidence that the number of hours of recharging undertaken by a user had an impact on the effectiveness of the intervention scheme. This result implies that the intervention is appropriate for all groups of EV users regardless of the amount of recharging undertaken.

6.5.8. Change in total hourly recharging frequency

Table 6-18 presents the total frequency counts for hourly recharging before and after the intervention period for the intervention group and the control group.

User group	**Total hourly recharging frequency**	
	Pre-intervention	Post-intervention
Intervention	6038	6264
Control	5854	5909

Table 6-18: Total hourly recharging frequency before and after the intervention

It can be seen that there was a similar amount of recharging before the intervention period for both the control group and the intervention group. A fisher exact test gives the chi-squared statistic to be 0.29, which is not significant at a 95% confidence level. There was a 3.7% increase in total hourly recharging events for the intervention group, compared to a 0.9% increase for the control group. The significance of this is that there is no evidence to suggest that offering financial incentives increased the overall amount of EV use that was taking place, reflected in the fact that there was no significant change in total recharging during the post-intervention period for participants.

6.5.9. Intervention Participant Responses to Questionnaire

This section presents SwitchEV participant responses to the questions that were posed at the end of their trial period relating to interventions. Overall, of the 21 intervention participants, only six users offered written responses to the open-ended section of the questionnaire. As this sample size is low, it is acknowledged that there may have been some issues not revealed through this analysis.

The **first question** ‘were you motivated to recharge at night once a financial incentive was offered?’ received six responses. Five users said that they were motivated to recharge overnight. An example response is;

“The incentive led me to be bothered to look at the manual to see how it could be done, and did make overnight charging a priority in a way that it would not otherwise have been. So yes, it changed my behaviour.”

One user disagreed, responding;

“We were not more motivated to recharge at night once financial incentive was introduced. As we use the vehicle for business purposes recharging is the responsibility of the user and the car will be connected for recharging by the user whenever the user has finished with it regardless of what time of day they finish.”

This response suggests that the financial incentive was not appropriate to override the practical operation of an EV as a pool car. However, the incentive did seem to have had a positive influence on the driver in raising awareness of the associated benefits. Given that the Organisation Pool users, as a group, did not significantly change their recharging behaviour, it can be speculated that this might have limited behavioural changes for more than just this one user.

The **second question** asked of drivers, ‘was it easy or difficult to change your behaviour’, received five responses. All five drivers stated that it was easy for them to change. An example response was;

“For my circumstances, this was very easy, since my main driving activities were based around a regular commuting pattern.”

The analysis of the intervention participants found no evidence of a change in the relative usage of recharging infrastructure by location. Whilst users with home recharging delayed this into the off-peak hours, they did not statistically significantly change the proportion of hours recharging at non-domestic infrastructure. This infrastructure was still used on-peak, in the same way as it was used before the financial incentives were offered.

Therefore, whilst drivers responded that it is not difficult to change how they use their home recharging infrastructure, they seem to either have difficulty in reducing, or not choosing to reduce, their non-domestic recharging usage. This was explored further by **question three**, which asked users ‘were there any practical barriers preventing you from recharging at night?’, of which six users responded.

Two users mentioned the public recharging infrastructure membership scheme, charge your car, as presenting a barrier;

“So, do financial incentives work, in my opinion, yes, but to a degree it depends on the nature and mechanism. Change the management of public charging-I view the move to pay as you go charging will impact this significantly. It would certainly change my charging habits to avoid public charging.”

The issue of the need to recharge on return to base as a policy for pool vehicles was highlighted as a barrier to behavioural change;

"Practical barriers as mentioned, i.e. vehicle user connects recharging once they return to office; this could mean recharging starts during the day or later in the evening. As a result user behaviours and use times are the main barrier."

This is further evidence that endorses the practical issues that can impact on the recharging operations of the EV due to company policy.

The role and function of smart meters was explained to users as part of the post-trial questionnaire. Users then responded to the statement 'smart meters would make it easier for me to recharge during the off-peak hours'. The results are illustrated in Figure 6-23.

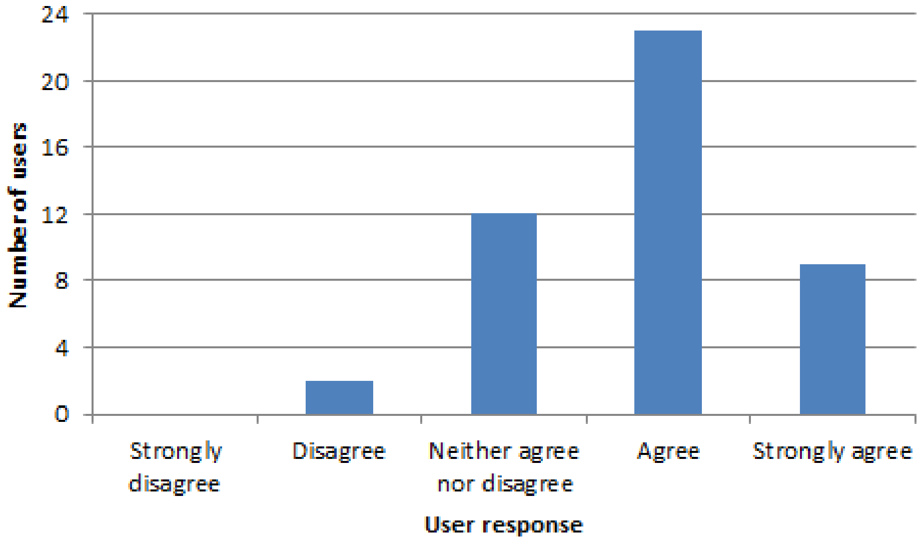

Figure 6-23: Users responses to the post-trial statement smart meters would make it easier for me to recharge during the off-peak hours' (n = 46)

73% drivers stated that smart meters would make it easier for them to recharge during the off-peak hours, those users selecting 'strongly agree' and 'agree'. Although most drivers have not had any experience of using a smart meter, this highlights the important role they can play in managing electricity demand due to EV recharging. Only 4% 'disagree' with this statement, which may be explained by the perceived need to recharge at non-domestic infrastructure during peak hours to complete daily trips, the influence of the NE PiP membership scheme and organisations with the 'always recharge the EV at base' policies.

Workplace recharging posts without timers presented a barrier to off-peak recharging. If the user did not have an in-vehicle timer, then the only way to recharge off-peak would have been to manually plug in the vehicle recharger at midnight.

The impact of the NE PiP membership scheme also was found to have an influence on drivers. All intervention participants were asked to respond to the statement ‘I would recharge more at home, off-peak if I had a smart meter and the existing NE PiP membership access scheme for non-domestic recharging posts’. They were also asked to respond to the statement ‘I would recharge more at home, off-peak if I had a smart meter and pay as you go (PAYG) standard fees for parking and electricity at non-domestic recharging posts’. The responses can be seen in Figure 6-24.

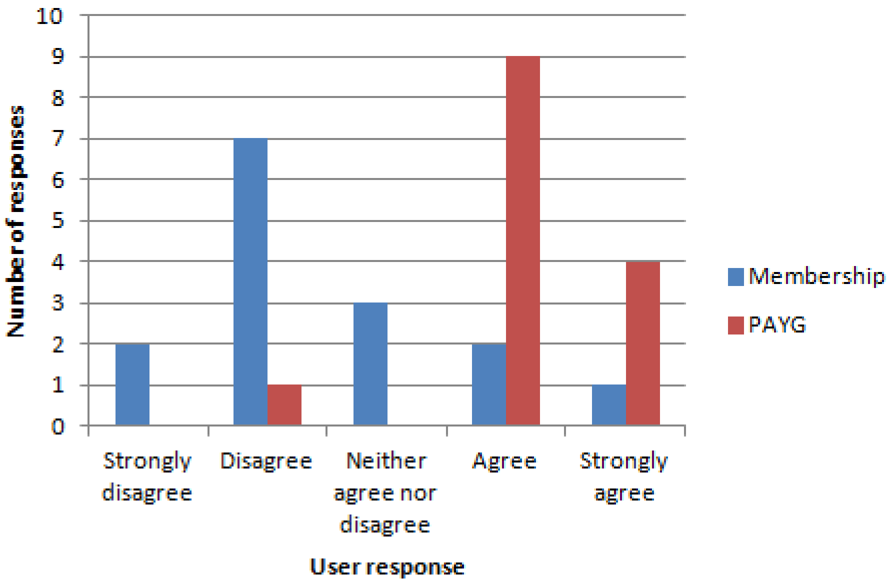

Figure 6-24: Post-intervention attitude to recharging infrastructure access scenarios (Membership scheme n = 15 and PAYG n = 14).

It can be concluded that, with the existing NE PiP membership scheme, 60% of the respondents are reluctant to recharge during the off-peak. On the other hand, 93% of users either ‘agree’ or ‘strongly agree’ when asked about if they would complete more recharging at home during the off-peak hours if a pay-as-you-go access mechanism for non-domestic recharging infrastructure was adopted.

This was confirmed by the fact that some drivers recharged off-peak if incentivised, but in this region did not increase the proportion of their recharging taking place at home.

However, when asked about if they would complete more recharging at home during the off-peak hours if a pay-as-you-go access mechanism for non-domestic recharging infrastructure was adopted. Combined with the focus group discussion regarding the NE PiP network, it can be concluded the membership scheme is one of the key barriers to encouraging off-peak recharging of EVs. Therefore, this research endorses the PAYG access to public posts as a policy tool that should be considered, as financial incentives and smart meters at home did not shift recharging away from the perceived 'free' public infrastructure network.

6.5.10. Critique

The use of open ended questions does not lead to statistically significant results. However, this exercise has provided useful insights that have endorsed the earlier quantitative results.

6.6. Summary of Key Findings from the Intervention Analysis

- **There was no change in behaviour observed for users in the control group**

The users in the control group did not make any statistically significant changes to their recharging behaviour. Neither were observed changes in the proportion of hours recharging off-peak; the proportion of off-peak recharging by location; the relative usage of recharging infrastructure by location nor the carbon content of electricity during EV recharging. This meant that any change in behaviour could be attributed to the intervention process.

- **Intervention participants did not change their relative usage of recharging infrastructure**

There was no evidence that the intervention participants changed the proportion of recharging they completed at each recharging location, they just moved their home recharging into the off-peak hours. This proves that, in the North East region, financial incentives alone were not an effective financial tool to shift recharging demand between locations.

- **Home was the only location in which financial incentives moved demand into the off-peak hours**

At all locations other than home, there was no statistically significant change in the proportion of recharging taking place during the off-peak hours. At home, there was almost a 23% increase in off-peak recharging. Hence other incentives are required in order to persuade them to do things differently at work or on Ne PiP infrastructure.

- **The NE PiP network limited the effectiveness of interventions**

Drivers did not statistically significantly change their behaviour at non-domestic recharging infrastructure because they were not sufficiently incentivised to do so. The perceived ‘free parking’ and convenience of the non-domestic recharging infrastructure reduced the effectiveness of the electricity reimbursement as an incentive.

7. Conclusions and Recommendations

7.1. Introduction

Increased electricity demand due to the anticipated growth in the EV market could locally overload power grids if recharging occurs during the on-peak times of the day. Furthermore, the carbon content of electricity is high during the on-peak hours, due to an increase in the use of coal as a power generation source. Current UK policy is to use smart meters, devices which can delay recharging events, in conjunction with financial incentives in order to manage recharging demand. However, this policy had not been tested in a region with a high density of non-domestic recharging infrastructure with a membership access scheme. Therefore, the aim of this research was to quantify the resulting recharging demand profiles and subsequent carbon content of electricity used in order to quantify the effectiveness of financial incentives and to understand why drivers utilised the recharging infrastructure as observed. This provided a fundamental understanding of how future policy can be shaped to ensure that power demand loads on the electricity network due to EV recharging can be managed during times of the day when low carbon electricity is readily available.

This research was conducted as part of the SwitchEV trial, a real world trial in the North East of England. This trial was chosen because it was the only region with a high density of non-domestic recharging infrastructure with a membership access scheme. Recharging events and GPS locations were obtained through in-vehicle loggers. There were 140 users of Nissan and Peugeot vehicles that were considered for analysis in this thesis. 23 were private, 43 were Organisation Individual and 74 were Organisation Pool users. There were 16,105 recharging events in total. In terms of recharging location, 588 events (4%) were at fast chargers, 2017 (13%) at home, 8575 (53%) at public locations, 1681 (10%) at other locations and 3244 (20%) at work.

Recharging demand profiles were defined for each driver. A hierarchical cluster analysis, using the ward linkage method with the squared Euclidican distance optimisation metric, was used to group drivers into clusters. The number of clusters specified for this analysis was determined by extracting all clusters with an Eigenvalue greater than one.

Within these trials, interventions were conducted at the midpoint of a sample of 21 SwitchEV participants. Drivers were contacted via email and offered a 50% reimbursement of the value of the electricity used to recharge their EVs during the off-peak hours. 21 drivers agreed to take part, and were subsequently supplied with information regarding reimbursement rates, environmental benefits and advice on how they can change their behaviour. An equivalent control group of 21 users were selected from those users not taking part in the interventions. Recharging data of individual drivers were split into pre-intervention and post-intervention periods. Statistical tests were then undertaken to determine whether changes in the proportion of recharging taking place during the on-peak hours, both overall and by location, were significant. Also tests were undertaken to determine whether there was a change in the proportion of recharging taking place at each location during the post-intervention period. Additionally, the change in the carbon content of electricity for recharging events was compared for the post-intervention time period for both participants and the control group.

Key themes impacting driver behaviour were obtained through post-trial written responses to specific questions regarding EV recharging and focus group transcripts. Thematic analysis was used to identify key discussion points. Post-trial questionnaire results were used to assess driver opinions regarding EV recharging. In the remaining sections of this chapter the key findings and main conclusions resulting from this research are presented in turn.

7.2. Users Recruited and Data Collected from SwitchEV

- **SwitchEV users were not representative of the general population. However, they compared favourably to early adopters of EVs. Vehicle usage was considered to be representative.**

The SwitchEV driver sample was not representative of the population of the North East of England as a whole. Typical SwitchEV users were; male;

employed full time in professional roles; with a salary/income above the regional average; between the ages of 36 and 55 and married. However, the SwitchEV participants were similar to the recipients of the National ‘Plug-in Car’ grants, suggesting that these users were representative of the early adopters of EVs in the UK.

Furthermore, 84% of users stated that they took part in SwitchEV due to environmental concerns. This compares to 66% of the British general public expressing concern about climate change (Department of Energy and Climate Change, 2013a). However, vehicle usage was representative of the general distribution of drivers in the UK.

Overall, the implication of this conclusion is that the behaviour of drivers in this study can be considered representative of the potential population of future EV owners.

7.3. Analysis of Driver Recharging Profiles Observed during Pre-Intervention Stage of Trials

- **Five recharging profiles were observed during the pre-intervention period for all drivers and the relative number of each user type differed significantly between these recharging demand profiles.**

The five recharging profiles were named in reference the time of day of their recharging peak. Large morning profile peaked at 13% of total frequency, between 08:00h and 09:00h; the small morning recharging profile peaked at 9%, between 10:00h and 11:00h; the end of working day profile peaked at 12%, between 15:00h and 16:00h; the early evening profile peaked at 9%, between 17:00h and 18:00h and the late evening profile peaked at 10%, between 22:00h and 23:00h.

9% of private, 47% of Organisation Individual and 14% of Organisation Pool users were allocated to the large morning recharging profile. The small morning profile consisted of 26% of the private, 30% of the Organisation Individual and 42% of the Organisation Pool users. The end of working day recharging profile was the only profile in which only one user type was present, namely 30% of the Organisation Pool users. The early evening recharging profile consisted of 34% of private, 19% of Organisation Individual and 14% of Organisation Pool users. 30% of private, 4% of Organisation Individual and 5% of Organisation Pool users recharging demand followed the late evening recharging profile. The allocation of different user types into recharging profiles was significantly significant.

This highlights the importance of understanding the characteristics of different types of owners of EVs in any given area. Power grid operations can use this knowledge to more effectively manage EV recharging profiles; by understanding EV purchasing patterns in a given region, anticipated recharging demand can be more confidently predicted. However, the profiles observed in other regions might not be the same as those observed in SwitchEV if different access mechanisms to non-domestic recharging infrastructure and/or different electricity tariffs are in place.

This is pertinent because predictions made in the reviewed literature do not generally suggest multiple profiles either within a given region or depending on recharging infrastructure development and access. Kang and Recker (2009), Mullan *et al.* (2011) and Wang *et al.* (2011) all made predictions assuming that, under a given recharging infrastructure and smart meter provision (or lack thereof), there would be only one predominant recharging profile. This study essentially represented one scenario i.e. a well-developed non-domestic recharging infrastructure with no smart meters in which all drivers had access to a large network of non-domestic recharging infrastructure. Therefore, in any given region, there are likely to be different recharging demand profiles that reflect the characteristics of the policies implemented. Also there will be a need for tailored management of demand by power infrastructure operators.

- **Recharging demand profiles were different to those observed in CABLED and MINI E trials. More on-peak recharging overall was observed. At home, less recharging took place during the off- peak hours.**

Recharging in these profiles took place predominantly during the on-peak hours, and at non-domestic recharging locations. For the large morning profile only 10% of the total frequency of recharging took place during the off-peak hours. Off-peak recharging accounted for 6% of the total recharging frequency for users following the small morning profile; 1% for the end of working day recharging profile and 7% for the early evening profile. However, the late evening profile recorded the highest proportion of off-peak recharging, with 22% taking place during the off-peak hours. Recharging at home accounted for 4% of early morning; 10% of late morning; less than 1% of end of working day; 18% of early evening and 36% of late evening total hourly frequencies. This was less than in other real world trials.

The CABLED study suggested that 62% of EVs would be recharged at home, overnight (Bruce *et al.*, 2012), a finding consistent with the MINI E trials (BMW Group, 2011). This supported the Office for Low Emission Vehicles (2011) suggestion that the bulk of EVs recharging needs to take place off-peak at home that outlined. However, the research reported here has indicated that recharging will not take place primarily off-peak unless the correct policy environment is in place. Additionally, the proportion of recharging taking place at the public recharging infrastructure was higher in SwitchEV. The amount of recharging at public recharging posts for the five profiles observed in this study varied between a minimum of 37% and a maximum of 75% of the total number of recharging events. The highest proportion of off-peak recharging was by those users allocated to the late evening recharging profile, in which only 22% of recharging frequency occurred during the off-peak hours compared to 62% in CABLED and almost 100% in MINI E.

The recharging demand profiles by location can be compared. The first stage of this comparison was to convert the units from CABLED and MINI-E into the percentage frequency of recharging values that were used in the SwitchEV data analysis. To convert the data from CABLED, the hourly values for electricity demand per car kWh for both home and work recharging were summed and divided by the total to give a percentage of demand per car, which is comparable to the % recharging frequency as a measure of the relative demand placed on the network. Similarly, the number of cars being charged per hour from MINI E were summed and divided by the total number of cars recharging per hour over the day to obtain an estimate for the percentage of car-hours of recharging taking place during any given hour.

The comparison between home recharging profiles can be seen in Figure 7-1.

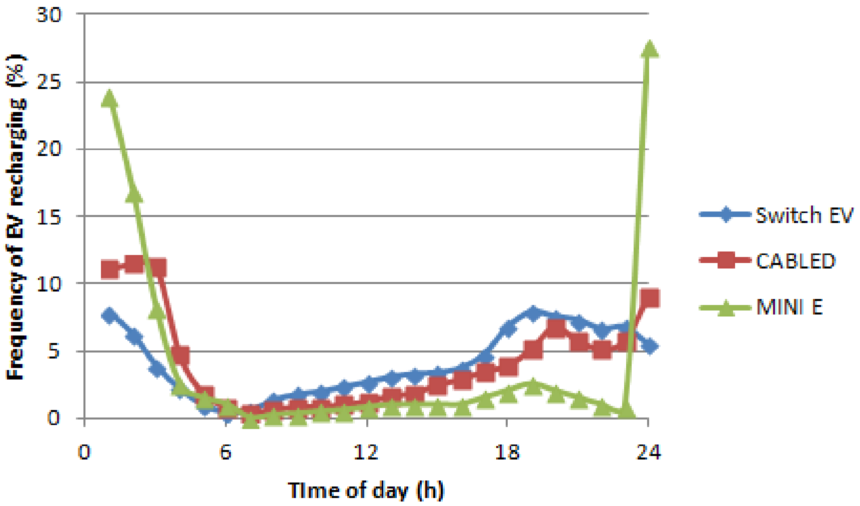

Figure 7-1: Home recharging profiles for SwitchEV, CABLED and MINI E users

The Home recharging profiles observed in SwitchEV followed the same general trend as CABLED and MINI E, with recharging peaks taking place in the evening. The frequency peak in SwitchEV was matched more closely by CABLED, with peaks of 8% and 7% respectively. MINI E followed the same trend, but a large peak was noted at midnight. The likely explanation for this difference was that MINI E users were given home recharging units which were pre-programmed to start recharging at midnight, and would require a user to select an override to recharge immediately. As vehicles typically arrive home from the working day at around 18:00h, the drivers likely did not have a reason to override the default midnight recharge setting.

The comparison between work recharging profiles can be seen in Figure 7-2.

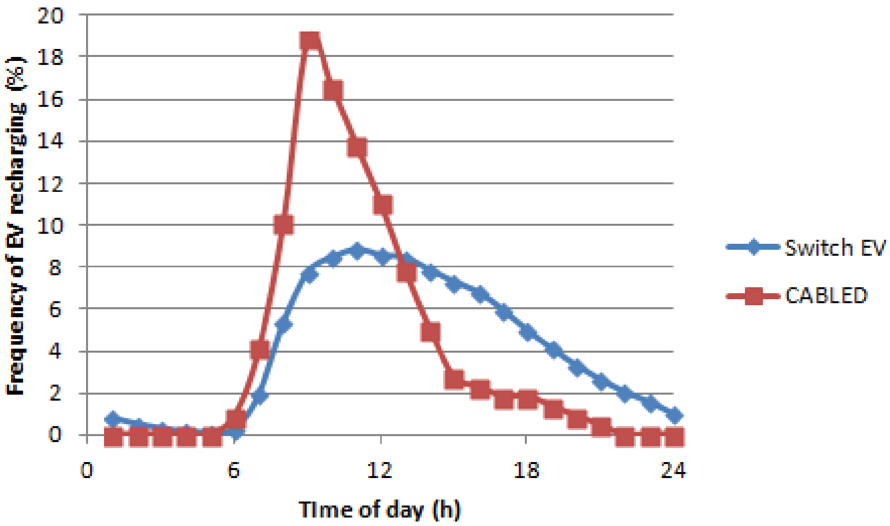

Figure 7-2: Work recharging profiles for SwitchEV and CABLED users

MINI E users did not have access to workplace recharging. Therefore, SwitchEV work recharging is compared to CABLED work recharging. The broad trend of a peak occurring before midday was observed in both studies. However, the magnitude of the peak frequency was 19% in CABLED, occurring at 09:00h, compared to a smaller peak of 9% at 11:00h for SwitchEV users. Although data from CABLED are not available, it can be speculated that this larger morning peak in demand was due to vehicles bring driven home at the end of the working day and being plugged-in upon return to work the following morning.

- **Habitual behaviour, the membership access scheme to the NE PiP network and a need to recharge to complete daily trips were found to influence recharging profiles. Smart meters and pay-as-you-go access to non-domestic recharging policy are required in future to manage demand more effectively.**

Through focus groups, it was revealed that most drivers follow habitual recharging routines. Some of the recharging habits observed were enforced by their organisations, whereby a policy was implemented in which the EV must start recharging immediately on return to base. This was suggested in focus groups, and proven empirically.

The NE PiP network played a key role in influencing recharging demands for SwitchEV drivers, and helps to explain differences between SwitchEV and other real world trials. Overall, the conditions in the North East of England were not conducive to off-peak recharging of EVs. There were over 600 non-domestic recharging posts in the region, compared to 36 in CABLED and home only recharging in MINI E (BMW Group, 2011; Bruce *et al.*, 2012). As a result of this relatively dense infrastructure network, SwitchEV vehicles were within 5km of a recharging post for 90% of their travel time and within 20km of a recharging post 99% of the time during their journeys in the region (Blythe *et al.*, 2012). Coupled with the fixed annual membership fee and perceived free parking, on-peak recharging was attractive. This was backed up by SwitchEV focus group discussion, which indicated that public recharging infrastructure, and particularly in Newcastle city centre, was considered to be convenient.

This provides evidence that the development of a high density public recharging infrastructure for EVs, combined with financial incentive of a fixed fee membership access scheme, induced on-peak recharging that would not otherwise have occurred. This is backed up by the work by Weiller (2011), which proposed that infrastructure access would influence the recharging behaviour of EV drivers.

Furthermore, some users perceived the low costs associated with using the NE PiP non-domestic recharging infrastructure as being ‘free’. This clearly suggests that the membership scheme incentivised EV recharging when it may not have been necessary.

7.4. Conclusions from User Interventions

- **There were no significant changes in recharging behaviour within the control group.**

There was no significant change in the percentage of recharging taking place before or after the off-peak period for the control group users as a whole. Also there was no significant change in the proportion of the relative number of hours of recharging recorded at each of the recharging locations for the users as a whole. This test was repeated for users of home and work recharging, as not all users had access to recharging infrastructure at these locations. Again, no significant difference in off-peak recharging was observed at either location. Consequently, for the control group, there was no shift in the carbon content of electricity during EV recharging.

The implication of this was that any changes in behaviour when considering the intervention participants could be attributed to the intervention process and not any other external factor.

- **The only change recorded post-intervention was for intervention participants with home recharging access. A median increase of almost 23% of recharging was shifted into the off-peak hours at home.**

For the intervention group as a whole, there was a significant shift in recharging towards the off-peak hours with a percentage point increase of 2.3% in the median number of off-peak hours per user.

However, the only location in which a significant increase in the relative number of hours of off-peak recharging was recorded was at home. For users with access to home recharging, there was a median percentage point increase in the number of hours recorded during the off-peak hours of 22.7% whilst, once the interventions were completed, this increased to a median of 41.9%.

At home, there was a median decrease of 27.3% percentage points of recharging time in the evening (18:00h – 24:00h), a statistically significant decrease of-0.7% in the proportion of recharging taking place on a morning (06:00h to 12:00h); with no significant change in the proportion of afternoon recharging. The intervention process was most successful in shifting evening recharging into the off-peak hours, but had minimal or no impact on recharging that took place on a morning or during the afternoon.

The results of the intervention highlight the current limitations of the plans outlined by the Office for Low Emission Vehicles (2011) by demonstrating that changing, or influencing, driver recharging behaviour is not as straightforward as offering financial incentives and rolling out smart meters. Additional policy innovations are required in order to create an overall economically sound environment in which smart meters and financial incentives play a more effective role than they did in this study.

- **Interventions did not shift recharging to home from non-domestic locations.**

In terms of the relative usage of infrastructure at each of the locations for the intervention participants as a whole there was no significant change in the relative number of hours of recharging recorded at each of the locations. This was true regardless of access to home or work recharging infrastructure. Despite this, in general, drivers stated that it would not be difficult to change their recharging behaviour with the availability of the appropriate technology and economic model.

- **The NE PiP membership scheme and the policy of some organisations to recharging the EV on return to base limited the effectiveness of financial incentives as a recharging management tool.**

The NE PiP membership scheme was found to be a disincentive to recharging at home. When asked how drivers would respond to the same intervention if it was combined with a switch to PAYG access to the non-domestic recharging infrastructure, 13 of the 14 respondents indicated that they would be more likely to recharge more at home and less at non-domestic locations.

Some drivers reported that their organisation has a policy of recharging their EVs immediately upon return to base, which had a negative impact on some of the pool user's attempts to change their recharging behaviour. Business operations issues may make it difficult to manage pool user recharging demand profiles. However, smart meters could shift recharging from the end of working day profile into the off-peak hours as there would likely be no operational requirements for EV usage outside 08:00 hrs to 18:00hrs for most users.

This is a key adoption area for EVs, so is an important problem to solve. In future, as well as smart meters, there may be a need for smart management of EV use when integrated into company fleets. However, there is also the argument that, if an organisation has operational needs whereby the EV must be sufficiently recharged to complete near future trips, then this recharging would be difficult to move to a different time of the day. There is potential here to use historic data collected by fleet managers to derive forecasting algorithms to aid the optimisation of the time and duration of recharging actually required to fulfil the business needs whilst managing demand on the grid during peak times.

7.5. Key Recommendations Arising from the Findings of this Research

- **Need for smart meters to manage recharging demands**

All recharging profiles observed in this study had large, distinct peaks. This creates the need for this demand to be managed by either delaying it into the off-peak hours or spreading it more evenly throughout the working day. All demand peaks are important from a carbon content perspective. From a grid management perspective, it is less critical to manage workplace recharging. Evening peaks at work occur at the end of the day where, typically, demand is lower. Furthermore, many industrial sites have local power grids that are reinforced beyond those used to provide power to residential neighbourhoods.

Recharging demand peaks are predictable. Based on both the recharging profiles identified, and focus group discussion regarding recharging habits, drivers followed a routine that manifested in large peaks in demand at similar times of day. This can help infrastructure providers understand the recharging demands that they need to manage.

Smart meter technology can be implemented in the future in order to manage these loads. It is advised that all EV users have home recharging units installed with the functionality to delay recharging into the off- peak hours. This should be encouraged via the use of off-peak electricity tariffs. This could allow evening peaks, which place a significant demand on local networks at a time when an existing peak is occurring due to increased residential demand as individuals arrive home from work, to be moved to less intensive off- peak hours. Furthermore, dedicated workplace recharging infrastructure with smart meter functionality should be encouraged for organisations if EVs are parked on workplace premises overnight.

- **Pay as you go access to non-domestic infrastructure should be implemented long term**

The NE PiP scheme has removed the incentive for drivers to follow the off-peak recharging behaviour outlined in government policy. The combination of the convenience of parking and a lack of out of pocket cost has encouraged drivers to maximise their usage of non-domestic recharging infrastructure. Previous analysis of the SwitchEV recharging data indicated that 7% of non-domestic recharging events during the on-peak hours were required for EV users to complete their daily trips (Higgins *et al.*, 2012). Although it is acknowledged that users might like to maintain a minimum amount of charge in the battery, to act as an ‘insurance policy’ in the event of unexpected congestion, or to allow the vehicle to be utilised quickly for unplanned trips or in emergencies, a pay-as-you-go access mechanism should be encouraged, in addition to a standard parking fee. This could discourage drivers using public infrastructure as a ‘free’ car park when recharging is not required.

Furthermore, in this region, the interventions and financial incentives alone were not an effective tool to properly manage recharging demand. It was found that recharging can be shifted from the early evening into the off-peak hours at home. However, the interventions did not shift recharging at non-domestic locations. Therefore, if recharging is to be shifted, the non-domestic recharging network should be pay-as-you-go. Drivers taking part in this study stated that this would make them more likely to recharge at home.

- **More widespread use of timing devices and smart fleet management of EVs are needed.**

In order for loads to be better managed, timing devices need to be more widespread to make it as easy as possible for user to change their recharging behaviour. Organisations should put in place mechanisms to manage their EV usage and subsequent recharging demands where possible. The current policy that many organisations have adopted is that EVs must be recharged immediately upon the EVs return to base. Such a policy makes it difficult for recharging demand to be managed.

Instead, EV usage that occurs during the on-peak hours should be scrutinised in order to establish whether it is possible to adopt the use of smart meters to deliver a shift in demand. This could again be made financially viable by offering off-peak tariffs.

As well as spreading the demand more evenly throughout the day, this could better delay the evening peak profile which, although not necessarily a problem from a grid capacity perspective, leads to higher emissions due to other energy demands on the grid at this time. As many pool users are required to plug-in immediately upon completing their trips, a user would need to be made aware that they are the last user of the EV in any given day to enable them to set this work recharging post to delay into the off-peak hours.

7.6. Limitations of this research and discussion of methodological approach

It is recognised that all vehicles leased to private users or organisation individual users were being used either as second cars, or that there was an existing petrol car in the household. Drivers did not hand over their existing car for the trial period. This therefore gave them an extra vehicle that, if they adopted an EV, might not be present. The implication of this is that some trips that might otherwise be completed using an ICE equivalent might have been completed in the EV due to the free parking or electricity, or the EV might have been used less than the ICE equivalent on longer trips. It is not possible to empirically examine this. However, it is acknowledged that this might have influenced vehicle usage.

In terms of the method of defining recharging profiles, the percentage recharging frequency was used as a metric. This was chosen to allow comparison with other studies and to indicate the recharging trends of users and groups. However, there are disadvantages with this approach the need to be acknowledged. The same number of days would be required in order to convert this metric into an actual demand. Therefore, this measure if limited in terms of converting the results into actual demand being placed on the power grid, rather than just indicating when this demand would occur. If this research were to be repeated, it would be advised to divide the aggregate power demand in each hour of the day by the number of days to obtain the average power demand per day. This approach could then be used to obtain actual power demands by day of the week, and remove periods where demand may vary, such as holidays. This would allow a greater understanding of behaviour. For example, it would be expected that pool vehicles would largely remain idle during the weekend, whereas private vehicles could have differing demands than they do on working days.

The absence of Organisation Individual users limits the outcomes of these interventions to Private users and Organisation Pool users. It would be recommended that further research be conducted on these user types. Furthermore, the small sample size of 21 users overall is recognised as a limitation of this study. This small sample size meant that in-depth analysis of the impact on users by their pre-intervention recharging profile was not possible. If there were more drivers taking part in this study, comparisons would have been made between users post-intervention behaviour, based on their pre-intervention recharging profile. This would have revealed whether groups of users with differing pre-intervention behaviour were all equally likely to change their recharging behaviour or whether specific groups were more likely to shift recharging into the off-peak hours than others.

The methodology used to compare the intervention results had limitations. It was useful because it compared before and after for the control group to check whether there was a significant change, then compared before and after for the intervention group. This allowed the relative change to be assessed. However, because of this approach, it was necessary to conduct an additional check regarding the number of hours of recharging recorded before and after between the control and the intervention group to ensure that there was no change in overall recharging demand between the groups due to the incentive being offered. For example, the financial incentive could have encouraged drivers to drive more, because the electricity was cheaper. This would not have been picked up by comparing the relative percentage point changes before and after for either the control group or intervention group in isolation. If the analysis were to be repeated, the before would have been compared with the before and the after compared with the after intervention data between the control and intervention groups as this approach would have been able to detect changes in overall energy use directly without the need for additional analysis.

Furthermore, it was not possible to conduct a cost of electricity sensitivity analysis due to the limited trial periods. For future trials, it would be recommended that drivers sign up to have smart meters at the beginning of the trial, and then to vary the cost off-peak electricity usage to determine how price signals can be best utilised to manage EV loads on the grid effectively.

Overall, it is considered that this number of users was sufficient to create a case for pay as you go public recharging in future years and also to highlight the overall problems policymakers may encounter when attempting to manage the recharging demands of EV users, especially in an environment with membership access to non-domestic recharging infrastructure. However, an element that was not possible to include in the intervention process was a feedback mechanism for drivers during the trial. There are examples in the literature where providing feedback to intervention participants has improved the likelihood of a behavioural change (Abrahamse *et al.*, 2007; Carrico and Riemer, 2011).

Additionally, it has been suggested that all future policies combine interventions and financial incentives with feedback mechanisms (Streimikiene and Volochovic, 2011). Therefore, it may be concluded that possibly the lack of an intervention mechanism limited driver’s motivation to further change recharging behaviour. However, the feedback from drivers indicated that there were significant barriers to behavioural change.

The NE PiP recharging infrastructure network and access mechanisms, lack of timing devices, practical recharging needs and company policy all reduced the effectiveness of the intervention. Also drivers were given information regarding carbon savings at the start of the trial, allowing them to assess their savings based on their known behaviour. Although this was not feedback at the point of use, this could have mitigated the impact of it not being providing.

7.7. Recommendations for Future Work

The overarching conclusion of this research is that, in the North East of England, EV drivers taking part in the SwitchEV trial did not complete the majority of their recharging during the off-peak hours, and financial incentives with timing devices at home were not sufficient to change this behaviour. Therefore, future work needs to be undertaken to understand how this problem can be addressed, as there is a risk of power grid overload as the EV market grows.

Access to the NE PiP non-domestic recharging network has changed from a flat rate membership access scheme to a pay as you go system at the end of June 2013. This presents an opportunity to determine the extent to which charging for the usage of public infrastructure impacts on the recharging behaviour of EV drivers. Data from NE PiP home and non-domestic infrastructure for drivers who have previously had access to the membership scheme, for approximately six months or more, before pay as you go was introduced, and six months or more after the introduction of the pay as you go scheme was available. This would provide the opportunity quantitative analysis on comparable timescales. As a minimum, January to June 2013 would be the membership scheme time period, and January to June 2014 would be the pay as you go time period. The total recharging time at each location would be calculated. This would then allow the proportion of recharging at public infrastructure, before and after the introduction of pay as you go access, to be calculated.

Also, based on the results of this study, there is a need to test the use of smart meters and financial incentives at work recharging infrastructure. This would determine the extent to which it is possible for pool vehicle recharging profiles to be delayed. This is important because, as indicated by the interest in pool use vehicles by organisations in the North East of England, workplace-based vehicles are likely to form a significant number of EV sales. Therefore, the morning and end of working day recharging profiles observed by users in this study could form a large proportion of the total UK EV fleet recharging demand in the future.

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9. Research Dissemination

9.1. Journal Publication

Robinson, A.P., Blythe, P.T., Bell, M.C., Hübner, Y. and Hill, G.A. (2013) 'Analysis of electric vehicle driver recharging demand profiles and subsequent impacts on the carbon content of electric vehicle trips', Energy Policy, 61, pp. 337–348.

9.2. Conference Papers

Robinson, A.P. (2013) 'An analysis of electric vehicle driver recharging demand profiles by time of day and subsequent carbon content from the SwitchEV trials in the North East of England', *Universities' Transport Studies Group*. Oxford, UK.

Robinson, A.P., Blythe, P.T., Bell, M.C., Hübner, Y. and Hill, G.A. (2012) 'Use Of Intelligent Vehicle Logger Technology To Track Electric Vehicle User Recharging Behaviour', *Intelligent Transport Systems World Congress*. Vienna, Austria.

Robinson, A.P., Hill, G.A., Hübner, Y. and Blythe, P.T. (2012) 'Investigating the potential to influence the electric vehicle users' recharging behaviour to reduce well to wheel carbon emissions', *Electric vehicle Symposium 26*. Los Angeles, California.

Robinson, A.P., Blythe, P.T., Bell, M.C., Hill, G.A. and Hübner, Y. (2012) 'Analysis of electric vehicle user recharging behaviour to quantify the impact of recharging times on the well to wheel carbon emissions of electric vehicle journeys', *Universities' Transport Studies Group*. Aberdeen, UK.

9.3. Awards

The paper 'An analysis of electric vehicle driver recharging demand profiles by time of day and subsequent carbon content from the SwitchEV trials in the North East of England' was awarded runner up for the Smeed prize for the best student paper at UTSG 2013.