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Electricity load estimation and management for plug-in vehicle recharging on a national scale prior to the development of third party monitoring and control mechanisms

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Electricity load estimation and management for plug-in vehicle recharging on a national scale prior to the development of third party monitoring and control mechanisms

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ABSTRACT

In accordance with the main aim of the study, a widely accessible, modifiable tool was created for parties interested in maintaining the national electricity supply network and parties interested in informing policy on plug-in vehicle adoption schemes and recharging behaviour control. The Parry Tool enables the user to incorporate present limits to plug-in vehicle recharging demand scheduling as imposed by the state of present technology (no third party mechanism for monitoring and control of recharging), present human travel behaviour needs and existing patterns in electricity usage; into the investigation of the impacts of recharging demand impacts and the design of mitigation measures for deflecting (parrying) worst case scenarios.

The second aim of the project was to demonstrate the application of the Parry Tool. The multidisciplinary/interdisciplinary information gathered by the Parry Tool was used to produce national demand profiles for plug-in vehicle recharging demand, calculated using socioeconomic and travel behaviour-estimated population sizes for plug-in eligible vehicles and vehicle usage patterns, which were added to existing national electricity demand for a chosen test week – this was the first scenario subsequently tested. The information gathered by the Parry Tool was then used to inform the design of two demand management methods for plug-in vehicle recharging: Recharging Regimes and weekly recharging load-shifting – these were the second and third scenarios subsequently tested.

Unmitigated simultaneous recharging demand in scenario 1 (all vehicles assumed to recharge at home upon arrival home every day) severely exacerbated peak demand, raising it by 20% above the highest peak in existing demand for the year 2009 over half an hour from 58,554 MW to 70,012 MW – a challenge to the generation sector. This increased the difference between daily demand minima and maxima and made the new total demand have sharper peaks – a challenge for grid regulators.

Recharging Regimes in scenario 2 split the estimated national plug-in vehicle populations into groups of different sizes that started recharging at different times of the day, with the word ‘regime’ being applied because the spread of start times changed over the course of the test week from workdays to weekend. This avoided exacerbation of the peak and reduced the difference between daily demand minima and maxima by raising minima, providing a load-levelling service. Scenario 3 embellished the Recharging Regimes with workday-to-weekend recharging load-shifting that therefore took better advantage of the often overlooked weekly pattern in existing demand (demand being higher on workdays than weekends), by allowing partial recharging of a segment of the plug-in vehicle population.

Limited consideration of the impact of changing vehicle energy usage (for which distance travelled was assumed to proxy in this study) showed that the more vehicles used their batteries during the day, the better the levelling effect offered by Recharging Regimes. Greater utilisation of battery capacity each day, however, can also be assumed to lessen the potential for workday-to-weekend load levelling, because load-shifting depends upon vehicles being able to partially recharge or defer recharging to later days and still meet their travel needs plus keep a reserve State Of Charge (SOC) for emergency and other unplanned travel. Whilst altering vehicle energy usage did not change the finding that unmitigated simultaneous recharging exacerbated existing peak demand, it was noted that when limited mileage variation was considered this sharpened the profile of total demand – the rise and fall of the new peak far steeper than that of the original peak in existing demand.

The Parry Tool combines a series of integrated methods, several of which are new contributions to the field that use UK data archives but may potentially be adapted by researchers looking at energy issues in other nations. It presents a novel fossil-fuel based justification for targeting road transport – acknowledging energy use of fossil fuel as the originator of many global and local problems, the importance of non-energy use of petroleum products and subsequent conflicts of interest for use, and a fossil fuel dependency based well-to-wheel assessment for UK road transport for the two energy pathways: electricity and petroleum products. It presents a method for the recalculation and ranking of top energy use/users using national energy use statistics that better highlights the importance of the electricity industry. It also presents the first publicly documented method for the direct consultation and extraction of vehicle-focused statistics from the people-focused National Travel Survey database, including a travel behaviour and household income-based assessment of plug-in vehicle eligibility, used to scale up to national estimates for battery electric and plug-in electric hybrid vehicle (BEV and PHEV) national population sizes.

The work presented here is meant to allow the reader to perceive the potential benefits of using several resources in combination. It details the Parry Tool, a framework for doing so, and where necessary provides methods for data analysis to suit. It should however be noted that methods were kept as simple as possible so as to be easily followed by non-specialists and researchers entering the field from other disciplines. Methods are also predominantly data-exploratory in nature: **strong conclusions therefore should not be drawn**. Rather, the work here should be seen as a guideline for future work that may more rigorously study these combined topics and the impacts they may have upon plug-in vehicle ownership, usage behaviour, impacts of recharging upon the national network and the design of mitigation measures to cope with this new demand.

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- How patterns in peaks and demand are not uniform across the network at the local level and that hybrid patterns in net demand at where lines join up have to be met by the line that feeds them.

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I wear this ring as a symbol of the promise I made that today
To stand beside you, as your equal and your friend
To trust, honour and respect you always
To share with you your joy and your pain
And in the darkest times to support, comfort and protect you
To treat you with compassion and understanding,
For as long as we both shall live.
All that I am, I give to you,
All that I have, I share with you,
And I will love you always.

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NOMENCLATURE/ABBREVIATIONS

ACS	Average Cold Spell
AEB	Aggregate Energy Balance
AER	All Electric Range
BBC	British Broadcasting Company
BERR	Department for Business, Enterprise and Regulatory Reform
BEV	Battery Electric Vehicle
BRLSI	Bath Royal Literary and Scientific Institution
BST	British Summer Time
BWT	British Winter Time
CABLED	Coventry and Birmingham Low Emission Demonstrators
CH4	Methane
CHP	Combined Heat and Power
CHPA	Combined Heat and Power Association
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO2	Carbon dioxide
COx	Oxides of Carbon e.g. CO2
DECC	Department for Energy and Climate Change
DERV	Diesel Engine Road Vehicle fuel
DfT	Department for Transport
DUKES	Digest of UK Energy Statistics
DVLA	Driver and Vehicle Licensing Agency
ESDS	Economic and Social Data Service
FBHVC	Federation of British Historic Vehicle Clubs
FCEV	Fuel Cell Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
FCV	Fuel Cell Vehicle
FFV	Flexi-Fuel Vehicle
FIT	Feed In Tariffs
GHG	Green House Gases
GJ	Gigajoules
H2	Hydrogen
HES	Hospital Episode Statistics
HGV	Heavy Goods Vehicle

ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IPCC	International Panel on Climate Change
ktoe	Kilotonne of oil equivalent energy
kWh	Kilowatt hours
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organisation
NEDC	New European Driving Cycle
NGET	National Grid Electricity Transmission plc
NHS	National Health Service
NOAA	National Oceanic and Atmospheric Administration
NOx	Oxides of Nitrogen e.g. NO2
NTS	National Travel Survey
O3	Ozone
OCEV	Office for Low Emission Vehicles
PHEV	Plug-in Hybrid Electric Vehicle
PLG	Private and Light Goods vehicle
PM10	Particulate Matter with a diameter in the order of 1 x 10-10 m
SD	Standard Deviation
SOC	State of Charge
SOx	Oxides of Sulphur e.g. SO2
SPSS	Statistical Product and Service Solutions (officially IBM SPSS)
SQL	Structured Query Language
SRC	Short Rotation Coppice
SYS	Seven Year Statement
TSGB	Transport Statistics Great Britain
UCZ	Urban Clear Zone
UK	United Kingdom
UKRES	United Kingdom Renewable Energy Strategy
USA	United States of America
V2G	Vehicle-to-Grid electricity flow
VAT	Value Added Tax
VOC	Volatile Organic Compounds e.g. Benzene

CHAPTER 1: INTRODUCTION

This chapter outlines the aims of this project, the research questions thus posed and the integrated methods, sources of data and analytical tools used to answer them. Appropriately mentioned thereafter are the contributions made to the field by this thesis.

1.1 PROJECT AIMS

Use of energy plays a crucial role in modern day living. Where to find it, how to convert it into other forms that enable transport or use, how to transport it and to where, who needs it and why, how it is used and the benefits or drawbacks of using one energy pathway relative to another, are all hot topics worthy of study for their importance to the continuation of civilisation. It is a substantial topic area interconnecting multiple disciplines and there are many problems in need of solutions. From an environmental and social science perspective, there are several fundamental gaps to be found in present day research that revolve around:

- Improper focus on green house gas (GHG) emissions and carbon footprints as primary motivations for switching road transport from petroleum products to electricity, ignoring particular importance of non-energy uses of fossil fuels, especially petroleum products
- The founding of national estimates for plug-in vehicle ownership that do not incorporate purpose-designed data analysis of the extremely overlooked National Travel Survey database [1]
- The founding of demand management measures for plug-in vehicle recharging that predominantly involve third party monitoring and control without consideration of public acceptance of (or refusal to adopt) these technologies, at a time when concern for privacy is regularly a feature of today’s news
- The creation of recharging demand management measures that consider only diurnal patterns in existing electricity demand and the need to avoid existing peaks, instead of using a combination of vehicle specifications and travel behavioural analysis to investigate how to make recharging demand compliment existing demand patterns over compatible timeframes

As such it became evident that some form of widely accessible, modifiable tool might be useful to parties interested in maintaining the national electricity supply network, and also for parties interested in informing policy on plug-in vehicle adoption schemes and recharging behaviour control. Such a tool would ideally provide, all in one place, integrated together:

- A sound philosophical, multidisciplinary basis for
    - Why non-energy use of fossil fuels must be prioritised and fossil fuels – especially petroleum products – conserved for this purpose
    - Why the choice of alternatives to fossil fuels is complicated by their use not only as energy sources, but as sources of chemical compounds used for energy (storage as well as carriers) and non energy purposes (like Hydrogen) along an their pathway from source to user
    - Why road transport constitutes a primary target for change given the relative magnitude of its use relative to other sectors, in combination with the type of energy the sector uses (petroleum products)
    - A simple well-to-wheel analysis comparing petroleum products and electricity energy pathways for road transport, but on a novel basis: fossil fuel dependency
- A review of key specifications for presently and imminently available plug-in vehicles in the UK
    - To inform national estimates for plug-in vehicle ownership eligibility based on price and mileage ranges
    - To enable the choice of example vehicles whose specifications could then be used to build national recharging profiles to consider the impacts of recharging
- A method by which to extract vehicle-focused travel behaviour statistics from an expansive but people-focused national database: the National Travel Survey (NTS) [1] including:
    - The extraction of socioeconomic and travel behaviour-based estimates for vehicles eligible for replacement with plug-in kinds (using price and mileage range averages from the review of plug-in vehicle types mentioned above) that are then scaled up to national estimates for ownership using national licensing statistics for UK road transport
    - The extraction of vehicle travel behaviour statistics for those vehicles deemed eligible for replacement with plug-in vehicles for

use in modelling potential recharging behaviour and defining constraints (specifically ‘recharging windows’: the period of time between which a vehicle is not in use and can be recharged)

- A review of UK national electricity demand that
    - Selects an appropriate test week from historical data for testing the impact of the national estimates of plug-in vehicles, and
    - Profiles the usage patterns that plug-in vehicle recharging demand must ideally be managed to compliment

Such a tool would enable the user to investigate and incorporate present limits to plug-in vehicle recharging demand scheduling, as imposed by the state of present technology, present human travel behaviour needs and existing patterns in electricity usage, into mitigation measures for deflecting (parrying) worst case scenarios.

The creation of this tool – the Parry Tool – became the main aim of the study. A second aim of the study was to demonstrate the applications of the tool, including use to inform the design of scheduling for plug-in vehicle recharging demand. Fig. 1.1 explains how the aims of the project are integrated into the Parry Tool and its applications, over the chapters of this thesis.

1.2 RESEARCH QUESTIONS

As noted in the last section, there is need for a tool that would be of use to parties interested in maintaining the national electricity supply network and informing policy on plug-in vehicle adoption schemes and recharging behaviour. This tool – the Parry Tool – was created to enable the user to investigate and incorporate present limits to plug-in vehicle recharging demand scheduling as imposed by the state of present technology, present human travel behaviour needs and existing patterns in electricity usage; leading to mitigation measures for deflecting (parrying) worst case scenarios. The Parry Tool was thus required to answer the following primary research questions:

1) How many UK vehicles might be substituted with plug-in versions (battery electric vehicles – BEV, or plug-in hybrid electric vehicles - PHEV) and how many cannot be substituted and must remain internal combustion engine vehicles – ICEV?
2) When would it be best to schedule new loads from plug-in vehicle recharging and what should constitute an ideal test week?

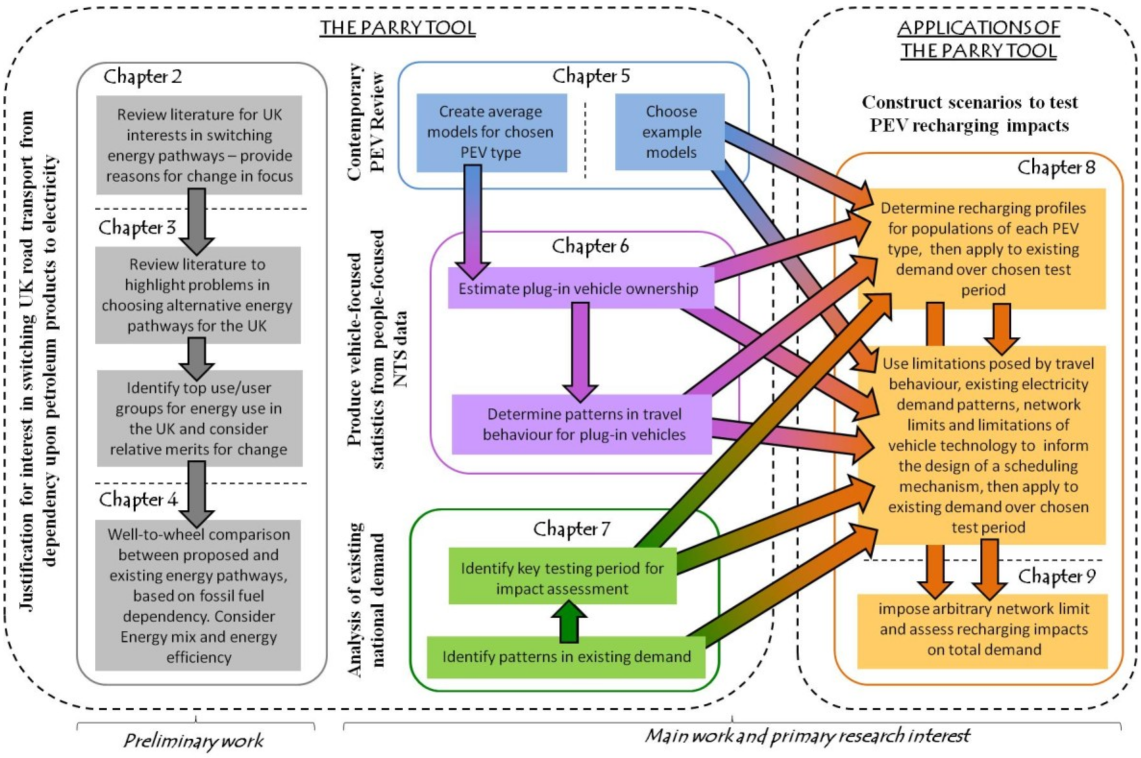

Fig. 1.1. The Parry Tool and its applications: different sections are labelled with the chapters that contain the requisite work and reflect the listed aims of the study. Arrows indicate the transfer of information from one chapter or stage of a chapter to another. The division of preliminary work from main work and primary research interests is also indicated at the bottom of the figure.

3) What are the travel behaviour patterns of vehicles that might be substituted with plug-in versions,
    a. What are their implied energy usage patterns?
    b. What are their implied recharging patterns?

The secondary aim of the project was to demonstrate the applications of the Parry Tool, including how the tool might be used to produce scheduling designs for plug-in recharging loads. This required the addition of a fourth and fifth primary research question to the above list to accommodate that aim:

4) How might the addition of recharging loads from plug-in vehicles alter the magnitude, timing, duration and shape of total national demand?
5) How might electricity demand from plug-in vehicle recharging be scheduled to complement patterns in existing demand?

These five questions are the primary research questions of the project and an outline of the integrated methods used to answer them will be provided shortly. The tool however also laid out preliminary work (see Fig. 1.1) to justify interest in converting road transport from dependency upon petroleum products to dependency upon electricity which required the review of energy use in the UK to provide a philosophical and multidisciplinary:

i. List of reasons for why non-energy use of fossil fuels must be prioritised and fossil fuels – especially petroleum products – conserved for this purpose
ii. Discussion of alternative energy pathways (the path travelled by energy from sources to end use) to highlight problems concerning conflicts of interest, the effective use of resources and reducing negative impacts when making changes to energy pathways
iii. Brief analysis of UK energy use in order to rank top energy use/user groups, followed by reasoned discussion for why road transport constitutes a primary target for change
iv. A simple well-to-wheel analysis comparing petroleum products and electricity energy pathways for road transport on a novel basis (fossil fuel dependency)

The above list constitutes the secondary research questions addressed as preliminary work in the Parry Tool.

1.3 SUMMARY OF METHODS

In this project a series of methods extracting basic statistics from a number of resources have been integrated together to form a tool – the Parry Tool. Preliminary work, answering the secondary research questions justifying interest in road transport and the conversion of road transport from petroleum products to electricity dependency, is also included. The main purpose of the Parry Tool, however, was for it to be used by parties interested in maintaining the UK electricity generation and supply system and interested in informing policies on the adoption of plug-in vehicles and control of their recharging behaviour.

The study and thus the Parry Tool, is focused upon plug-in vehicle recharging on a national scale using current plug-in vehicle types, travel behaviour and electricity demand, not future projections. Limited quantitative and qualitative assessments are instead combined to paint a broader picture for how cross disciplinary knowledge, from the different resources used in the study, can be drawn together in a useful and strategic way.

Methods used were kept as simple as possible, so as to be easily followed by non-specialists and researchers entering the field from other disciplines. **Strong conclusions should not be drawn**. Rather the work here should be seen as a guideline for future work that may more rigorously study these topics. It also should be noted that the methods are predominantly data exploratory in nature.

With only one exception (the collection of plug-in vehicle specifications relevant to the study) all data has been acquired from pre-existing archives, collected and collated by established authorities such as National Grid plc, and government bodies such as the Department for Transport (DfT). A summary of all the methods employed is provided below.

1.3.1 Justification Of Interest: Methods (Preliminary Work)

Preliminary work was performed in order to ensure that there was justification for the primary research interests of the project. Justification for the shift in focus of research away from symptoms (e.g. Green House Gases, climate change, respiratory illness) towards the root cause – fossil fuels (specifically energy use) – and premise for prioritising reduction of use and conservation of fossil fuels for non-energy pathways, is given by qualitative assessment (literature review) in Chapter 2, with minor use of figures for UK energy use taken from the Digest of UK Energy Statistics (DUKES) reports [2]. A brief literature review of alternative energy pathways then highlights some of the problems for proposing change by giving relevant examples of conflicts of interest, questionable effective use of resources and other problems associated with how negative impacts of energy use of fossil fuels are avoided.

A novel analytical method is then included in the Parry Tool (presented in Chapter 3), the purpose of which was to identify and rank key energy use/user groups by UK energy usage, by regrouping energy use listed in the Aggregate Energy Balance (AEB) table in the DUKES report for the year 2008 [3]. It was necessary to produce this AEB recalculation method for regrouping of energy use from the Aggregate Energy Balance in the DUKES report because otherwise energy industry use is separated from energy used in transformations (for example conversion of fuel into electricity and refinery of petroleum products from primary oils). Together with other segregations in the table, this makes it difficult to appreciate just how much energy goes into the provision of electricity without regrouping.

The electricity industry, the domestic sector and road transport were subsequently highlighted as key energy use/user groups. A discussion then follows that considers these key energy use/user groups in the context of the literature review in Chapter 2, the overview of alternative energy pathways by literature review at the start of Chapter 3, and other literature reviewed regarding the prospects for change for these top use/user groups. This then provides the reasoning for why road transport in particular represents a prime target for altering its energy pathway: road transport is a top energy use/user group, whose energy use is almost entirely dependent upon fossil fuels, in particular petroleum products – the significance of which to modern civilisation for non-energy use purposes is highlighted in Chapter 2.

A second analytical method was then used in Chapter 3, the purpose of which was to consider the prospect of switching the energy pathway for road transport from petroleum products to electricity, in the context of fossil fuel dependency. This was done by calculating and comparing energy mix and energy efficiency associated with electricity and petroleum products energy pathways for road transport, through a fossil fuel dependency-focused well-to-wheel assessment.

Figures from Chapter 2 for the analysis of the Aggregate Energy Balance table in the DUKES 2008 report [3] were used to establish energy mix, efficiency and fossil fuel dependency for the well-to-tank part of the assessment. This included some very basic consideration of the proposed ideal changes to the proportions of renewable energy resources included in road transport fuels and electricity generation as stated in the UK Renewable Energy Strategy [4].

Figures from the Transport Statistics Great Britain 2008 report [5] for vehicle population sizes and fuel usage were then used to calculate energy usage of the vehicle population in the same energy units as were used for the well-to-tank part of the assessment (ktoe). Comparative conversion efficiencies to kinetic energy for diesel and petrol engines versus electric motors (from Cullen et al [6]), were then used as proxies for vehicle energy efficiency at-point-of-use for the two pathways, to complete the well-to-wheel comparison. The result of which provided the final justification for interest in the conversion of road transport from dependency upon petroleum products, to dependency upon electricity.

Subsequently a literature review of prospects for road transport highlights the additional benefits offered when road transport and the electricity industry energy use/user groups are linked together, via a switch in energy pathway for road transport from petroleum products to electricity. This concludes the preliminary work and investigation of secondary research questions.

1.3.2 VEHICLE SPECIFICATIONS METHOD

This was the only method that incorporated data collection. Data was collected by a literature review of online resources such as vehicle manufacturer websites, plug-in vehicle news outlets and vehicle manufacturer-administrated Facebook fanpages. The selection of specifications was limited to plug-in vehicles that were already or imminently expected to be marketed to UK consumers. The selection was also limited by the need for compatibility with criteria other resources used for the project – namely the National Travel Survey – which affected the type of plug-in vehicle investigated (data collection was specifically focused on four-wheeled vehicles).

The first purpose of collecting specifications was to produce an 'average model' BEV and a PHEV with regards to price and mileage range, in order to inform estimates for plug-in vehicle ownership in the UK. Ownership estimates were to be determined in the next analytical method, based on the DfT's National Travel Survey (NTS) [1], so distance and income thresholds were set so as to correspond to the criteria available in the survey. The second purpose of collecting specifications was to allow the selection of an example PHEV and BEV for later use in the construction of recharging loads. Real (not average) vehicle specifications were deemed more robust to use for demonstration of the Parry Tool's applications.

1.3.3 NTS STATISTICS EXTRACTION METHOD

This is a primary contribution of the thesis to the field: the provision and demonstration of a method for extracting vehicle-focused statistics from a people-centred survey: the National Travel Survey (NTS) [1]. The method had two purposes and so is divided into two parts in Chapter 6. The first purpose (Part 1) was to provide ownership estimates for PHEV and BEV eligible vehicles within the surveyed population of the NTS, based on household income and daily distances travelled, then to scale these up to national estimates for plug-in vehicles that could have been owned in the UK. The second purpose (Part 2) was to then provide basic statistics and basic contextual analysis of travel behaviour for those populations of BEV and PHEV eligible vehicles.

Part 1 used of Microsoft Access to make queries to select travel records for households earning above a given income threshold for potential ownership of the average BEV and PHEV models defined in Chapter 5. Maximum mileage travelled on any day of the travel week by vehicles belonging to those households was then used to divide those vehicles into PHEV and BEV eligible vehicles, based on thresholds defined by the average BEV and PHEV model defined in Chapter 5. These estimates were then proportionally scaled up to estimates for PHEV and BEV eligible vehicles in the national road transport population, using Driving and Vehicle Licensing Agency (DVLA) figures for vehicles licensed to drive on UK roads in 2008 from the Transport Statistics Great Britain (TSGB) report 2009 edition [7], for taxation classes comparable to ownership criteria used in the NTS [1].

Part 2 then used Microsoft Access to base queries on the travel records selected for BEV and PHEV eligible vehicles in Part 1, to ascertain some very basic statistics: average mileage, and average 'first departure from' and 'last return to' home times for each day of the week, for each type of vehicle. Further record selections were made to allow these statistics to be considered in the context of standard deviations and scatter graphs that visually demonstrate the greater variability of human travel behaviour in real life, around these average distances and times.

1.3.4 NATIONAL ELECTRICITY DEMAND PATTERN ANALYSIS METHOD

The main purpose of the very basic data analysis of half-hourly annual electricity demand data from National Grid [8] presented in Chapter 7, was to highlight what is already covered by literature: when the worst time of day, week and year would be to add a substantial new demand for electricity to the existing national electricity demand profile. This was then used to define and select an ideal testing period over which the addition of recharging demand and assessment of impacts should be made. The testing period was selected so as to broadly consider patterns in existing electricity demand, noting points of interest from the perspective of adding new demand, as to when and when not it would be ideal to do so. Recommendations arising from this were used later in Chapter 8 to inform the design of a recharging demand scheduling method.

A simple analysis was used in preference to the more complex grouping method for pattern identification provided Fan et al [9]. This was because the patterns of interest to this study are self-evident in the raw data, and what was not found elsewhere (and was considered to be of use here) was the analysis of the raw data in terms of maxima and minima in demand – diurnally, weekly and annually. This was used as a means for checking to see if there was any trend developing for demand to swing between greater extremes, as a further justification of the benefits and perhaps future need for load-levelling by carefully designed scheduling of new electricity demands.

1.3.5 CONSTRUCTING SCENARIOS METHOD

In Chapter 8, the information gathered from the other chapters, as part of the Parry Tool, are used together for the purpose of constructing three scenarios for the addition of plug-in vehicle recharging loads to existing national electricity demand. The first scenario simplistically builds recharging profiles for a population of PHEV and BEV, based on national-scale ownerships estimated from the NTS statistics extraction method (Part 1) in Chapter 6, recharging specifications for the example vehicles chosen in Chapter 5, and average 'return to' home times calculated in the NTS statistics extraction method (Part 2) in Chapter 6. These were added to existing demand profiles for a test week, chosen in Chapter 7 as based on the review of national electricity demand patterns.

The second scenario built upon the recharging profiles made for scenario 1 and used information gathered by the Parry Tool in a different way. A strategy for the design of recharging load management (based on current technology and therefore not assuming an advanced third party recharging monitoring and control system is in place) is exampled including the reasoning process, followed by the process for the construction a time-block based series of Recharging Regimes. These Recharging Regimes constitute another primary contribution to the field of study. The third scenario assumed that Recharging Regimes have been applied, but considered on top of these the potential for shifting recharging loads from workdays to weekends. The process for scheduling recharging durations in order to do this is included in Chapter 7.

1.3.6 RESULTS ANALYSIS METHOD

A very simple analysis of the different scenarios constructed is provided in Chapter 9. The analysis first provides demand profile graphs and tables for visual comparison of each individual scenario. The analysis then draws comparisons between different scenarios by plotting results for difference scenarios on the same graph or tabulating differences.

The arbitrary network limit is marked on each demand profile graph for each scenario. Analysis included the tabulation of the largest breaches of that network limit on each day of the test week for those scenario results to which this applies. Included in tables for those scenarios are the ‘at risk’ periods on each day – the lengths of time over which total demand would have been in breach of that arbitrary network limit. Tables are also provided for scenarios that employ load-levelling demand management (Recharging Regimes and workday-to-weekend shifting of recharging loads), that show impacts to minimum demand on each day of the test week.

For all scenarios individually and when being compared, impacts to the difference between daily maximum and minimum demand are also provided. Bar charts were constructed to show the absolute difference on each day. High-low plots show the direction of changes to the absolute difference between daily minima and maxima: If there is a widening of that difference it can be seen whether this is due to the maxima increasing or minima decreasing, if there is a narrowing of that difference it can be seen whether this is due to the maxima decreasing, or the minima rising. Additional tables are provided in the comparisons section of the analysis, to note comparative differences made to maxima and minima but also to show where applicable, the difference made by shifting recharging loads from workdays to weekends.

1.4 SOURCES OF DATA

By scope of the research questions, the Parry Tool was required also to rely on resources that provide nationally relevant information. The primary sources of data used were as follows:

- The Department for Energy and Climate Change (DECC) Digest of UK Energy Statistics (DUKES) reports [2]
- National Grid's half-hourly annual electricity demand spreadsheets [8]
- The Department for Transport (DfT) National Travel Survey, archived by the Economic and Social Data Services (ESDS) [1]

Plug-in vehicle specifications had to be gathered from a variety of resources. These included vehicle manufacturer websites, 'minisites' set up by manufacturers specifically to host information relating to a particular plug-in vehicle model, articles relating to plug-in vehicles from plug-in vehicle enthusiast websites, and Facebook fanpages for plug-in vehicles administrated by vehicle manufacturers. Interestingly all vehicle manufacturers looking to market plug-in vehicles in the UK maintained a Facebook presence at the time this study was conducted, but it should be noted that of all the resources used in this study, those used to gather plug-in vehicle specifications were the only non-static data resource used.

Vehicle manufacturers have a habit of modifying their websites – and sometimes their vehicle specifications – presenting new information, removing previous information, and switching their focus between national and international centres for information about their products. Information was often relocated and sometimes pages focused on a particular vehicle that had been set up separate to their main company website, were abolished completely at a later date.

References to online resources for vehicle specifications will be made at point of use in Chapter 5. References to other resources from which only singular or minor reference is made, will also be provided at point of use. Each of the bulleted resources listed above, however, deserves a short review and explanation because of the extent of their use in this study as will shortly follow. Please note that comparison is made between the NTS [1] and UK Time of Use Survey [10] as to their potential usefulness for the investigation of plug-in vehicle behaviour under '3.3.3 Drawbacks and Shortfalls of Literature Reviewed' in Chapter 3.

1.4.1 THE DIGEST OF UK ENERGY STATISTICS (DUKES) REPORTS

Frequent reference is made to a series of annual UK government reports known as the Digest of UK Energy Statistics (DUKES) in Chapters 2 to 4. All reports, from the newest to the oldest releases, are downloadable from the Department for Energy and Climate Change (DECC) website [2]. These reports represent a unique and expansive resource offering a great deal of insight into UK energy use and energy users whilst also enabling comparisons for mix and efficiency between the main energy pathways.

These reports use the non-SI unit of ‘thousands of tonnes of oil equivalent energy’ (ktoe). According to the International Energy Agency (IEA) [11] the unit ‘tonne of oil equivalent’ energy (toe) is an internationally recognised standard used to compare energy use in different forms and on very large scales such as energy use by different sectors within a nation. As usually stated under ‘Technical notes and definitions’ in the first chapter of each DUKES report:

> *“In common with the International Energy Agency and with the Statistical Office of the European Communities, the tonne of oil equivalent is defined as follows:*
>
> *1 tonne of oil equivalent = 107 kilocalories*
> *= 396.83 therms*
> *= 41.868 Gigajoules (GJ)*
> *= 11,630 Kilowatt hours (kWh)”*

- DECC, paragraph 1.28 from [12]

> *“This unit should be regarded as a measure of energy content rather than a physical quantity. One tonne of oil is not equal to one tonne of oil equivalent.”*

- DECC, paragraph 1.29 from [12]

Using the IEA website energy converter [13] it is possible to grasp the scale of energy use for the UK and thus show why the ‘toe’, specifically the unit ‘thousands of toe’ or ‘ktoe’ is preferred. For example according to the 2009 DUKES report by the DECC [14], in 2007 the total ‘primary demand’ for the UK was 235,738 ktoe. Using the IEA converter [13], this was would equal 9,869,878,584 GJ; meanwhile the smallest range of energy reported in most of the DUKES reports tables is of the order of 1 ktoe, equivalent to 41,868 GJ. Scaling figures to ktoe makes those figures easier to compare.

Other notes are made with regards to the specific use of the Aggregate Energy Balance table in the 2008 edition of the DUKES report [3] can be found in Chapter 3 where that particular table is heavily used.

1.4.2 National Grid Annual, Half-Hourly, National Electricity Demand Data

Free-to-use, half-hourly electricity demand data spanning the years from 2001 to date is published online by National Grid plc [8]. Time is not given in hours but in SETT periods, equivalent to half hourly intervals. No explanation for the exact translation of time into SETT periods was found after touring the National Grid website and the data itself, but correspondence with fellow academics and experienced fellows in the electricity industry suggested that 'SETT' was an abbreviation for "Settlement", the term "Settlement period" used for accountancy purposes. The following definition for settlement periods was used:

> *"Settlement Periods are always based on Local Time and Period 1 is always 0000hrs (midnight) Local Time. A Normal Day has 48 Settlement Periods, whereas a Short Day (clocks go forward) has 46 and a Long Day (clocks go back) has 50."*
>
> \- ELEXON, BM Reports help page at [15].

Prior to April 2001, data was collected daily, not half-hourly and so only data after this date was used in the project. For years subsequent to 2002, each year's data is split into two Excel spreadsheets[1]. The first spreadsheet for each year provides data from SETT period 1 on January 1st through to SETT period 48 on 30th July, the second gives data from SETT period 1 on 1st July through to SETT period 48 on the 31st December.

As stated by National Grid on their website [8] and within each Excel spreadsheet, the half hourly demand data are given in four formats. The format used for this study was BMRA (short for 'Balancing Mechanism Reporting Agent') data: Initial Demand Outturn (INDO) based on National Grid operational generation metering. It excludes Station Load, Pump Storage Pumping and Interconnector Exports and so most truly reflects the 'demand' placed on the supply system by British-based consumers of electricity.

Dates for time changeovers between British Winter Time (BWT) and British Summer Time (BST) are marked in the National Grid data where days that switch from BWT to BST have only 46 half-hour readings and where days that switch between BST to BWT have 50 half-hour readings. Dates for public holidays were acquired from www.timeanddate.com [16].

1.4.3 NATIONAL TRAVEL SURVEY (NTS) DATABASE

> *"The National Travel Survey (NTS) is the primary source of data on personal travel patterns in Great Britain. The NTS is an established household survey which has been running continuously since 1988. It is designed to monitor long-term trends in personal travel and to inform the development of policy.*

---

[1] Excel files for annual demand data are split into two files because prior to the release of Office 2007, Excel spreadsheets had insufficient columns or rows to cope with the full list of readings for an entire year.

> *The survey collects information on how, why, when and where people travel as well as factors which affect personal travel such as car availability, driving licence holding and access to key services.*
>
> *Since 2002, the Department for Transport (DfT) has commissioned the National Centre for Social Research to conduct the survey fieldwork. Data collection consists of a face-to-face interview and a one week self-completed written travel diary. Approximately 20,000 individuals, in 8,000 households, participate in the NTS each year."*

- DfT, from 'National Travel Survey Statistics' available at [17]

The NTS surveys travel behaviour across England, Scotland and Wales. Summaries of statistics drawn by the DfT from the NTS can be found at [17]. The NTS runs year round, sampling weeks from across the whole of each year and no single household as yet has been surveyed more than once. No other survey as comprehensive, covering so many variables or such a large area with so large a number of respondents that focuses upon travel behaviour could be found for the UK. The resolution of the statistical summaries provided online however was considered insufficient to answer the research questions concerning what percentage of people might be able to own and use a plug-in vehicle of particular specifications. The criteria for the summaries were not provided in sufficient detail, meanwhile the database itself is a far richer resource with a whole host of criteria to enable tailor-made queries to be performed.

In Fig. 1.2 the structure of the NTS database is shown. The records within the NTS database are layered so as to allow the definition of primary keys by linking specific groups of variables. In particular, 'H96 – Sample year', 'PSUID – PSU (Primary Sampling Unit) Identification Number' and 'H88 – Household reference number' when combined are unique for every household in the survey. Add to this 'I1 - Person Number' and a resolution down to information about single individuals within a household can be obtained, similarly so 'V1 - Vehicle Reference Number' allows distinction between different vehicles belonging to the same household. 'Trips' are journeys composed of several 'stages' that may have been made using different modes of transport, involving different people, each with its own start and end time. 'Stages' are the finest resolution available in the NTS.

The complete survey data is archived by the Economic and Social Data Service (ESDS) and is supplied free of charge to non-commercial users who agree to abide their user license. Once a license for use has been obtained, the latest edition of the survey can be downloaded in several formats.

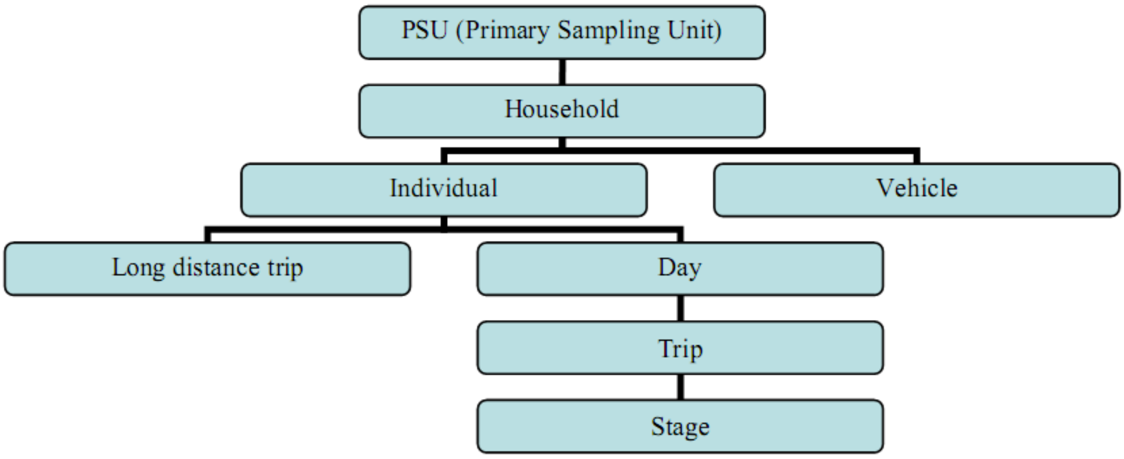

Fig. 1.2. Structure of the NTS database. Figure reproduced from page three of the ‘National Travel Survey (NTS) data, 2002-2008: User guidance’ PDF document that accompanied download of the database [1].

All together the NTS database totals is too large to open in Microsoft Access or Microsoft Excel, especially in earlier versions and not all users have access to high specification hardware to manipulate the full database. For this reason the ESDS fragments the database into 8 tab-delimited text files titled based on Fig. 1.2. Together the files total 662 MB. Each ‘.txt’ file has an accompanying Microsoft Word document detailing how many variables are contained, a list of the variables and all possible criteria. A list of the tab-delimited text files, their sizes, the number of variables for which they contain data, and example variables and criteria for each is provided in Table 1-1.

Each variable and the possible response criteria for each, is coded to save file space. For example ‘V87A - Engine Capacity (cc - banded)’ is coded ‘v87a’ in the .txt file and a response indicating a vehicle has an engine capacity of ‘Up to 1500’ is coded as ‘0’. Other variables do not have specific criteria (excluding those indicating e.g. that a participant did not answer), but can hold instead continuous integers as values in the .txt files. For example ‘Journey Start Time’ is column-titled in the .txt file for ‘trips’ as ‘JST’ and values vary as integers from ‘0’ minutes past midnight upwards (some return times for trips could be at an hour in the following day) as defined by individual respondents.

Files can be connected together in Microsoft Access by tying together variables that are duplicated between files. In Access these connections are called ‘relationships’ and the variables are called ‘fields’. ‘H96 – Sample Year’ and ‘PSUID – PSU Identification Number’ are fields present in every file for example and so form a bridge between all of them. For this study, the different files for the NTS had to be cross-linked through various fields because the information for all criteria of interest is not located in one file but spread between several. For example: a ‘trip’ made by an individual in the Trips file has a journey ‘purpose from’ and ‘purpose to’ and also has a related start time and end time.

Table 1-1: Dissection of NTS database.

File name	Size (MB)	No. variables	Example of variables contained
Psu	0.2	13	P2G - Government Office Region (GOR) e.g. 'West Midlands' and 'South West', P5A - Type of area (2001 GIS coding) e.g. 'Rural' and 'Urban over 250k' meaning urban with a population over 250,000.
Household	23.9	165	TWSDATE - Travel Week Start Day e.g. Tuesday, H19 – Bus distance to doctor (2002-2004) e.g. '14-26 minutes', H70A – Household Income e.g. 'Less than £25,000' per year, H61A - Household structure e.g. '2 adults, 3+ children'.
Individual	62.4	175	I2 - Relationship to Household Reference Person e.g. 'Spouse', I264 - Frequency of taxi/minicab use e.g. 'Once or twice a month', I329 - Main difficulty to do main shopping e.g. 'Poor information about public transport'.
Vehicle	6.4	30	V87A - Engine Capacity (cc - banded) e.g. 'Up to 1500', V91A - Vehicle Age e.g. '2-3 years', V112 - Company Car Summary e.g. 'Used for work/ no allowance'.
Trips	297.6	44	J24 - Journey Purpose From e.g. 'Home', J54 - Journey Start Time (minutes past midnight - unbanded) e.g. '635' would be 10:35 am, J62 - Total Cost of Public Transport Journey (banded) e.g. '500-999p'.
Stage	265.1	42	S2 - Mode of Transport e.g. 'Car', S18 - Private Vehicle Occupant e.g. 'Front passenger', S22 - Whose Vehicle? e.g. 'Non-Household veh.'.
Day	11.9	5	H88 - Household Reference Number e.g. '121', I1 - Person Number e.g. 'Person no.5', D1 - Travel Day e.g. 'Day 1'.
Ldj	10.8	27	LDJDay - LDJ Day of the Week e.g. 'Monday', L7 - Long distance journey purpose to e.g. 'Eat/drink', L8 - Mode of transport e.g. 'Air'.

The Trips file however does not have any fields[2] that indicate which household vehicle was being used to carry out journeys. A means for identifying the vehicle is only provided by linking the Trips file to the Stage file (which identifies whether or not the journey was made using a household or non-household vehicle) then the Vehicles file to determine which household vehicle performed the journey if it was a household vehicle.

There are a few further points to note when using the NTS regarding ideal sample sizes and the possible errors that can be expected to feature in the survey results:

---

[2] In Microsoft Access rows are called "records", columns are called "fields". See the following training tutorial for Microsoft Access 2007 at http://office.microsoft.com/en-us/access-help/get-to-know-access-2007-RZ010274013.aspx for further information.

> *“Because estimates made from a sample survey depend upon the particular sample chosen, they generally differ from the true values for the population. This is not usually a problem when considering large samples (such as all car trips in Great Britain), but may give misleading information when considering data from small samples, for example cyclists in a particular age band.*
>
> *In general, it should be remembered that for estimates of households, individuals and vehicles, unweighted samples of under 100 should not be used, while samples of under 300 should be used cautiously. For trip and stage estimates, even more caution should be exercised: samples of under 300 should not be used, whilst samples of under 1,000 should be used cautiously.”*

- Page 4 of the ‘National Travel Survey (NTS) data, 2002-2008: User guidance’ PDF document that accompanied download of the NTS database [1].

The sample sizes used in this study were not known until after the selection processes for differentiating between vehicles and assessing their travel behaviour was complete. None of the samples used in this study however involved less than 1000 vehicles, households, trips or stages.

1.5 ANALYTICAL TOOLS USED

Two analytical software tools were used in this study: Microsoft Excel and Microsoft Access from the Microsoft Office 2007 suite. These tools were selected for use because of their relative low-cost compared to more research-specialised alternatives, wide availability to researchers all over the world and the familiarity of these products that can be found across multiple disciplines within academic and non-academic professions. It was hoped that if the Parry Tool used such software tools, that familiarity with the software would be one less barrier to interested parties from varied backgrounds that might like to use it, allowing it to live up to the goal of being widely accessible.

1.5.1 MICROSOFT EXCEL 2007

MS Excel 2007 was used to handle:

- The recalculation of energy use/user groups from the Aggregate Energy Balance table of the DUKES report [3] in Chapter 3,
- The well-to-wheel fossil fuel dependency comparisons for the electricity and petroleum products energy pathways for road transport in Chapter 4,

- The simple analysis of annual half-hourly national electricity demand data from National Grid [8] for the review of national electricity demand patterns in Chapter 7,
- The construction of scenarios (including the construction of Recharging Regimes and workday-to-weekend load-shifting recharging schedules), and for the basic analysis of scenario results

Any basic mathematical calculations, for example the calculation of average mileage ranges and prices for plug-in vehicles during the review of plug-in vehicle specifications in Chapter 5, were also conducted in MS Excel. The spreadsheets were also used to archive additional cursory information as text in cells close to data inputs e.g. web addresses for source websites, reference materials and observational notes.

National Grid data [8] is actually already provided in the format of MS Excel spreadsheets, albeit split in two because older versions of Excel had limits to the numbers of rows and columns that prohibited display of an entire year's worth of demand readings. The 2007 edition of MS Excel however had an upgraded limit of 1,048,576 rows by 16,384 columns [18]. This made it possible not for whole years to be viewable in spreadsheet format, but for demand data for different years to be placed alongside one other for comparison, inserting graphical displays of the data for each for very fast visual inspections.

With no background knowledge of MATLAB but experience of handling spreadsheets and cell functions in MS Excel, MS Excel 2007 was certainly the most convenient software tool to use for conducting simple analyses and graphical displays of electricity demand but it was also potentially the better tool. Not only is MS Excel cheaper and far more familiar to a larger cross-section of people, but for smaller datasets (such as the electricity demand data used in this project) where it is practical to do so, visual inspection of raw data is easy and facilitated by tools such as conditional formatting for cell highlights.

For the construction of Recharging Regimes and workday-to-weekday load-shifting, visual inspection, cell functions and the ease with which information could be grouped, segregated, linked to other tabs (or even other spreadsheets) was particularly useful. Excel limitations became apparent when required to produce scatter graphs of selected travel records (proportionally a small sample of the NTS database [1] but still too large for Excel and the computer hardware used to handle well), for which MATLAB would probably have been a better tool.

1.5.2 MICROSOFT ACCESS 2007

MS Access 2007 was used to handle the NTS statistics extraction method, with only a few data exports and imports to and from Excel spreadsheets to carry out a vehicle numbering correction on the NTS vehicle information and to display graphs of travel behaviour at the end for providing additional context to the statistics gathered.

When the NTS data was downloaded from [1] for this study, it included all data for years spanning from 2002 to 2008 and was provided in two formats: tab-delimited text files which can be opened with various software including Microsoft Excel and Microsoft Access, or SPSS compatible files. At time of acquisition of NTS data, university-wide SPSS licenses were under renewal. Very limited training was available on how to use the software, with a likely wait of several months before the next basics tutorial. MS Access was used on the basis that some experience with MS Access and immediate accessibility was better than no experience with SPSS and a possible delay of access to data. The 'Microsoft Office Access Help' tool also proved very informative, easy to use and easy to understand.

Convenience, training and availability were the original stimuli for choosing to use Access, but these reasons also exampled very well how research can sometimes be limited both by accessibility of software and by lack of training. This then spearheaded the realisation that especially in the case of multidisciplinary work, which might not wholly be conducted by academia or parties with budgets for specialist software purchasing and training, that this might be a barrier to people who might otherwise use the Parry Tool. This then framed the whole study with a broad goal to do as much as possible, with as little as possible, as simply as possible.

Generally, however, it can be said that MS Access was fit for the purpose of the NTS statistics extraction method presented in this thesis, which involved the creation of a long chain of queries to select records, then select records from within that selection, repeating this several times to narrow down the records and criteria being investigated. SPSS is a powerful tool for statistical analysis of a sample that has already been selected, but it may not have been, in the end, the better choice for carrying out that repetitive selection process.

There were, however, notable problems with the application of MS Access in this study. These problems revolved around the fact that the NTS is such a huge resource, and the fact that just as the NTS is not designed to be dissected the way it has been used here, MS Access is not designed to be used in the way it has been used to carry out that dissection. Further benefits and drawbacks of using MS Access to handle the NTS and carry out the NTS statistics extraction method will be discussed as part of the project evaluation in Chapter 11.

1.6 CONTRIBUTIONS MADE TO THE FIELD OF STUDY

Listed below are the contributions of this project to the field of study of plug-in vehicles, in order of importance:

- **The NTS statistics extraction method**: A method by which to extract vehicle-focused travel behaviour statistics from the people-focused National Travel Survey (NTS) [1] including:
    - socioeconomic and travel behaviour-based estimates for vehicles eligible for replacement with plug-in kinds (using price and mileage range averages from a review of plug-in vehicle types), scaled up to national estimates for ownership using national licensing statistics for UK road transport
    - vehicle travel behaviour statistics for those vehicles deemed eligible for replacement with plug-in vehicles, for use in modelling potential recharging behaviour and defining constraints (specifically the ‘recharging window’: the period of time between which a vehicle is not in use and can be recharged)
- **Recharging Regimes**: A time-block approach to electricity demand management for plug-in vehicle recharging that prevents the exacerbation of existing demand peaks whilst offering load-levelling opportunities that could be implemented by vehicle owners as opposed to relying upon the existence of a complex third party recharging load monitoring and control mechanism
- **Workday-to-weekend shifting of recharging loads**: Incorporating partial recharging into Recharging Regimes so as to alter the distribution of recharging loads over weekly time periods to better reflect weekly patterns in existing electricity demand, adjusting recharging durations such that minimum requirements for next day’s driving are met, plus allowance for an emergency reserve
- **Introduction of fossil-fuel focused well-to-wheel analysis**: The comparison of electricity and petroleum products energy pathways for road transport in the context of fossil fuel dependency
- **The Parry Tool**: A tool that draws together information from and basic analysis of multidisciplinary resources to check justification for interest in the electrification of road transport, to inform plug-in vehicle load estimation and the design of recharging load management on a national scale, incorporating present limits to plug-in vehicle recharging demand scheduling as imposed by:

the state of present technology, present human travel behaviour needs and existing patterns in electricity usage, into mitigation measures for deflecting (parrying) worst case scenarios

- **An analysis method to find top energy use/users**: A method for regrouping energy use listed in the Digest of UK Energy Statistics (DUKES) Aggregate Energy Balance to provide a more useful dissection of purpose-centred energy use in the UK

1.7 CHAPTER 1 SUMMARY

This chapter has outlined the aims of this project, the research questions thus posed and the integrated methods, sources of data and analytical tools used to answer them. Contributions made to the field by this thesis have also been listed.

CHAPTER 2: THE IMPORTANCE OF FOSSIL FUELS

Presently there is a lot of interest in switching between different energy pathways: switching between sources, carriers or storage forms of energy along its path to final consumers. One particular group of energy types – fossil fuels – has become widely used because of their energy density and multi-functionality, being of use not only as sources of energy but as effective carriers and storage forms too. Interest in switching energy pathways usually focuses on fossil fuels, in particular to support efforts to reduce dependence upon them.

There are many reasons for that interest, but understanding the reasoning behind it is fundamental to shaping the solutions. It is important to have a sound philosophical reasoning behind any desire for a specific change *before* methods are considered. It is important to appreciate the big picture so as to avoid wherever possible the creation of more problems that result from improperly focused, improperly designed and/or improperly implemented solutions.

This chapter will thus explore fossil fuel dependency in the contexts of types of use, limitations of availability for fossil fuel and rising concerns for dependency upon this finite resource in terms of the security of supply of energy resources. Detrimental impacts arising from use are then considered. Together these considerations frame the argument as to why there is such a great concern for dependency on this particular resource. Drawn from these considerations are then provided eight reasons as to why reduction of use and conservation of fossil fuel should be the focus of research today, especially in the UK, not Green House Gas (GHG) emissions or related 'symptoms' arising in consequence of fossil fuel use.

2.1 FOSSIL FUELS: ENERGY USE AND NON-ENERGY USE

Fossil fuels have multiple uses and have, over time since their discovery both as a chemical feedstock and an energy reserve, become integral to modern societies around the world. They are used for energy purposes (e.g. transport, electricity generation, heating) via combustion processes and for non-energy purposes as ingredients in chemical processes [14].

Non-energy uses of fossil fuels contribute towards the production of medicines, paints, aerosols, insecticides, adhesives, fertilisers and plastics [19-22]. British Petroleum provide information on their website about the many other things for which fossil fuels – particularly petroleum and gas products – are essential, such as: the production of many cosmetics, types of clothing, carpets, varnishes, printing inks, detergents, food packaging and even some ingredients in mass-produced foods such as acetic acid [23]. Non-energy products of fossil fuels are thus extremely important towards the upkeep of modern societies and modern standards of living.

Calculations based on the "1.1 Aggregate energy balance 2007" table of the 2008 DUKES report [3] showed that in 2007 nearly 100% of coal, approximately 90% of petroleum products and approximately 99% of natural gas used in the UK was attributed to energy use (see Table 2-1)[3]. A review of the same table for the years 2009 and 2011, as viewable in the 2010 and 2012 DUKES reports, [12, 24], suggests these estimates have changed little over the past few years. As noted by Table 2-1, energy purposes are thus by far the largest use of fossil fuels in the UK, as is also true for the United States of America (USA) [19]. Note also that non-energy use of fossil fuels is almost exclusively dependent upon petroleum products, identifying a possible conflict of interest with other uses of that particular type of fossil fuel such as energy use by transport.

Table 2-1: Energy and non-energy use of fossil fuels for the year 2007 calculated using figures from the "1.1 Aggregate energy balance 2007" table of the 2008 edition of the DUKES report [3].

Fossil fuel	Proportion used for energy[1] purposes (%)	Proportion used for non-energy purposes (%)	Proportion relative to total fossil fuel used by the UK (%)
Coal	100.00	*Negligible (< 0.01)*	18.06
Primary Oils	90.38	9.62	41.15
Natural Gas	99.01	0.99	40.79

[1] Energy use for each fuel was calculated by subtracting non-energy use from the primary demand figure for each. Primary oils have to be refined into other petroleum products before they are used by any other sector than the ones that perform this function; as such non-energy use of petroleum products was divided by the primary demand total for primary oils.

2.2 FOSSIL FUELS: A FINITE RESOURCE

There is a general concern for dependency on fossil fuels in terms of future sustainability because they are a finite resource [25]. They are finite because rate of use far exceeds rate of natural production – rate of production taking of the order of millions of years to produce any one known reserve on the planet, rate of use leading to the effective depletion of that resource taking no more than a few thousand years. Various factors threaten to make future scarcity and dependence upon fossil fuel an even greater risk.

Developing countries are expected to be responsible for over three quarters of fossil fuel emissions by 2030, due to rapid economic growth rates and growing shares in energy-intensive

---

[3] In [3] energy consumption is usually measured in one of three different ways: primary fuel input basis, energy supplied basis and useful energy basis. The table mentioned uses the primary fuel input basis which includes energy used or lost in the conversion of primary fuels to secondary fuels and energy conversion losses by final users.

industries [26], indicating a sharp increase in energy use, therefore also a likely increase in demand for fossil fuels. Demand for fossil fuels for both energy and non-energy uses in the developing world will continue to increase following rising aspirations for quality of life [22].

The most recent edition of the DUKES report at time of writing (that for the year 2012) suggests that the prediction of decline in native production of fossil fuels in the UK has so far held true [12]. The nation grows more dependent upon imports, meanwhile there is expected to be increased competition for those imports. It is for this reason that the government White Paper on Energy [27] cited the following three reasons as to why the UK should seek to reduce dependency on fossil fuels specifically for the sake of energy security:

1) Native production of oil and gas is expected to decline over the next decade (the UK will become increasingly dependent on imports).
2) Imports cross many borders, making them vulnerable to stoppages (by accident or incident).
3) Most imports originate from increasingly politically unstable areas of the world.

Each of these factors is worsened by the prospect of declining availability of supply. According to England [28], the three themes listed above are expanded upon to argue that *conserving* fossil fuels should be the priority, given that over time their abundance will decline and alternatives must be found. In summary, England listed three motives for fossil fuel conservation:

1) The threat of lock-in to an alternative energy technology that is ecologically hazardous or economically unviable.
2) The threat of social crisis resulting from the incompatibility of present social institutions and a new energy technology.
3) The threat of rent-seeking oil wars to control dwindling petroleum reserves.

The timeframe over which this study has arched included a number of profound events internationally that have contributed to the energy debate and reinforced the reasoning for reduced dependency on fossil fuels whilst also compounding difficulties in switching to alternatives. The first influential event to note was the “Arab Spring” period of political unrest, starting in early 2011 across various countries in North Africa and the Middle East, that caused oil prices to fluctuate [12, 29] and the instability continues.

In March of the same year, mere weeks before military intervention in the Libyan civil war (included in the Arab Spring) by NATO forces began, a record-breaking magnitude 9.0 earthquake struck Tohoku in Japan. Aside from causing upwards of 16,000 deaths and making hundreds of thousands of people homeless [30] the subsequent tsunami caused damage to the one of Japan's largest non-fossil fuel dependent electricity generators; the Fukushima Daiichi nuclear power plant. This highlighted the dangers of natural disasters and risks they can pose to the various supply systems – energy and otherwise – that modern humans rely upon, but the tragedy also sparked waves of anti-nuclear rallies [31]. All of Japan's 50 nuclear reactors – previously responsible for around 30% of Japan's electricity supply – were shut down for maintenance following the earthquake, but the Fukushima incident reignited fears over nuclear power within Japan such that public sentiment was in favour of keeping them shut down [32].

The Japanese government now intends to make "... plans to utilise more renewable energy sources, increase investment in renewables and look for cheaper sources of LNG and other fossil fuels" [33] and indeed, "Tepco has had to sharply increase the amount of fossil fuels it imports after a government mandated shutdown of all nuclear reactors in Japan because of the nuclear crisis" [34]. The disaster also reignited fears about nuclear energy globally such that the German government declared in the same year that its nuclear power plants would be phased out of use by 2022 [35]. Concerns are being cited that this decision will also contribute to increased global demand for fossil fuels [36, 37].

Even so, not all countries are expected to curb dependency upon nuclear power. Some saw opportunity in increasing their dependency upon nuclear power, planning for surplus electricity to then be exported to countries adopting anti-nuclear policies who subsequently find themselves unable to make up for shortfalls in supply from native electricity generation. Shortly after the disaster and Germany's announcement to curb nuclear power, France sought to expand its nuclear power plans for the future [38]. However, even before the release of the draft report, French president Francois Hollande signalled a change of heart, pledging to cut the share of nuclear power in France's energy mix to from 75% to 50% by 2025 [39].

A draft report on an investigation by the European Nuclear Safety Regulators Group (ENSRG) to assess the readiness of Europe's reactors to cope with emergency events following the Fukushima incident [40], may be adding to public anti-nuclear concerns in Europe. The report for example stated that 24 out of the 145 reactors checked didn't have backup emergency control rooms, whilst 81 reactors did not have adequate equipment available for coping with severe accidents such as earthquakes or floods. For the UK, the report by the ENSRG stated that most nuclear power plants lacked an alternative emergency control room to use if the main one became contaminated by high radiation [41].

Public anti-nuclear sentiment isn't going away. At a recent anti-nuclear rally in the UK, one protester stated: "We will keep coming back until these plans for a new radioactive waste factory have been abandoned" [42]. This somewhat crude and false interpretation of the purpose of nuclear power stations may however harbour legitimate concerns over nuclear power. The poor ratio between a nuclear power station's useful service lifespan where it is generating electricity, versus the time it took to build and the time it takes to fully decommission such a plant, is noted in Fig. 2.1 reproduced from an article in New Scientist magazine [43] which cites the Vandellòs reactor in Spain as an example. The same article notes that there is a growing queue of reactors awaiting proper and full decommissioning.

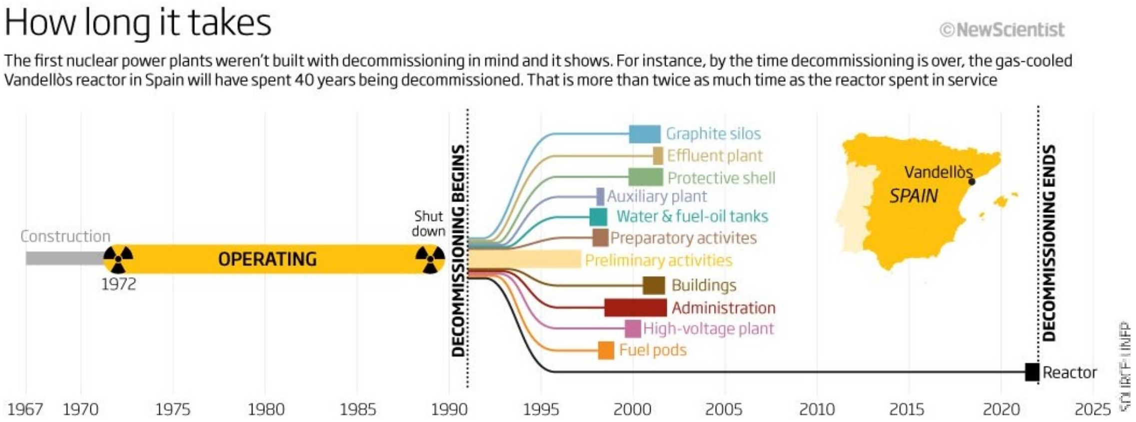

Fig. 2.1. "How long it takes" diagram featured in New Scientist article [43] © 2012 Reed Business Information Ltd, England. All rights reserved. Distributed by Tribune Media Services. Direct link: www.newscientist.com/data/images/archive/2855/28551402.jpg

These facts, alongside not-soon-forgotten memories of Chernobyl and now Fukushima, are not exactly conducive to convincing the general public that the people making decisions about nuclear power 'know what they are doing'. But if nations shift away from nuclear power, there are no resources that can yield the same scale of electricity generation as nuclear power - see Fig. 2.2 from [44] for a humorous illustration of the difference in energy density of different fuels. Fossil fuel dependent electricity generation is usually the first fall-back, meaning increased demand for that resource will follow.

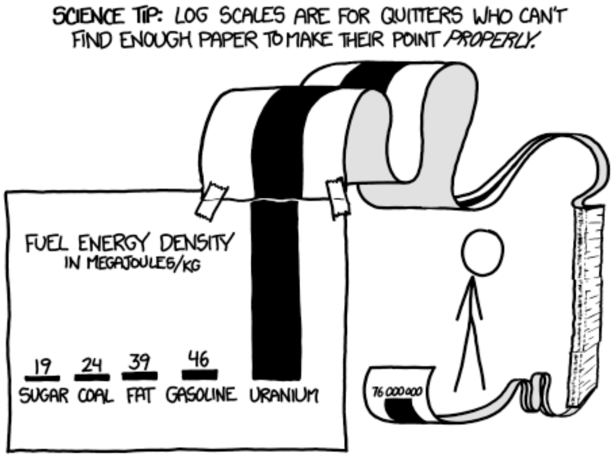

Fig. 2.2. Adapted from “Log Scales” comic strip from the xkcd webcomic [44] (used under creative commons license).

2.3 FOSSIL FUELS: DETRIMENTAL CONSEQUENCES OF USE

Discussions of the detrimental consequences of fossil fuel use usually focus on emissions tied to energy use, dividing such concerns along two primary scales of measuring impacts: ‘near term versus long term’ and ‘local versus global’. Energy and non-energy uses of fossil fuels have several stages from extraction through to refinery in common with one another, which thus incorporate similar human health and environmental degradation hazards. This part of Chapter 2 will mainly focus on the sorts of pollution that typically arise ‘at point of use’ as consequences of energy dependency upon fossil fuels.

Several types of pollution are associated with the combustion of fossil fuels for energy purposes. With respect to air pollution, the main polluting emissions attributed to the combustion of fossil fuels are [14, 45]:

- ‘CO_x’ (Carbon oxides: CO and CO_2)
- ‘SO_x’ (Sulphur oxides: SO_2 and SO_3)
- ‘NO_x’ (Nitrogen oxides: NO and NO_2)
- VOC (Volatile Organic Compounds – such as 1,3–butadiene generated by incomplete combustion and Benzene found in petrol which readily evaporates at room temperature)
- PM10 (particulate matter with a diameter of the order of magnitude of 10^{-10} m) as well as other ‘ultrafine particulate matter’

Lead (Pb) was also a significant concern as it was previously added to UK petrol as an anti-knock agent. When research indicated harmful effects in children, unleaded petrol was introduced and leaded petrol eventually banned [14]. Further to this, some of these pollutants are involved in other atmospheric chemistry reaction chains contributing to the formation of secondary pollutants. For example: NO_x and VOC are involved in the production of ground-level Ozone (O_3) [46, 47].

2.3.1 NEAR-TERM AND LOCAL IMPACTS: AIR POLLUTION

> *"Bad air quality costs the nation £8.5-20bn per year via poor health, it says and can cut life expectancy by years."*
>
> \- Black, BBC News Environment Correspondent in [48]

In the UK, health costs in terms of the provision of medical professionals, treatment facilities, equipment and prescriptions are primarily paid for by the government via the National Health Service (NHS). This means that the UK government has a strong incentive to produce policies that reduce common health risks and address their causes, including air pollution. Some emissions constitute direct health risks e.g. CO (Carbon monoxide) and ultrafine particulates [44]. Emerging research also suggests that the prevalence of many atmospheric pollutants generated by the combustion of fossil fuels affect emergency hospital admittances for people suffering with headaches and migraines [49-52].

Ultrafine particulate matter is associated with heart disease, cardiopulmonary disease, atherosclerosis development, cystic fibrosis, chronic lung disease and some forms of cancer, with possibly no 'safe level' for exposure [53]. Ultrafine particulate matter emissions are associated predominantly with combustion the heavier fuels used for heat and power e.g. particularly coal [47, 54], but also with the combustion of transport grade fuels [55], in particular diesel [47].

Emissions mix and magnitude can also be attributed to fuels pre-combustion. The ultrafine particle emissions produced during the mining of coal, for example, can contribute significantly when considering emissions from electricity generation where coal features as an energy source [47]. Also, while ascribed to the same class of pollution, the type of emission produced may differ between sources. For example: ultrafine particulate matter released during coal mining is not the same as that released for coal combustion and may differ again between different forms of combustion [47].

High up in Earth's atmosphere – the stratosphere – Ozone (O_3) is a useful ultraviolet (UV) radiation blocker. Unfortunately it is also a potent GHG and more importantly at ground level, “high levels of ozone increase susceptibility to respiratory disease and irritate the eyes, nose, throat and respiratory system” [14]. VOC are released by both vehicular combustion (usually as a product of incomplete combustion) of ethanol and by petrol (gasoline), but even when emitted in the same amount by each the relative contribution of each to ozone formation can vary from one compound to another due to differences in their reactivity and structure [47]. VOC can also be harmful in and of themselves. For example: Benzene is a VOC that is highly carcinogenic to humans, emissions of which come from the distribution and combustion of petrol [5].

Types and proportions of emissions from the combustion of fossil fuels are dependent upon fuel type and are influenced by the purpose for which fuels are used, for example SO_x emissions are particularly associated with generation of electricity from coal-fired power stations [46, 54, 56]. SO_x emissions from the combustion of fossil fuels (e.g. in various transport vehicles, electricity generation) affects the lining of the nose, throat and airways of the lung especially amongst people who suffer from asthma and chronic lung disease [14].

2.3.2 LONG-TERM AND GLOBAL IMPACTS: CLIMATE CHANGE

Fossil fuel emissions have indirect impacts over large geographical areas and long time scales. Of particular interest over the past decade has been the connection between these and climate change. GHG – ‘greenhouse gases’ – are so named for their spectral properties when exposed to electromagnetic radiation of being reflective to infrared radiation but transparent to visible light. GHG when present in Earth’s upper atmosphere work as panes of glass do in a green house. Although this ‘global warming’ effect is a natural phenomenon, consensus is growing that anthropogenic emissions are increasing atmospheric GHG abundance and thus increasing their impact, bringing about changes in climate at local and national scales.

‘Superstorm’ Hurricane Sandy left over eight million homes and businesses without power and in New York, flooded subways and cut off emergency services such that 50 homes burned when fire-fighters were unable to reach them [57]. Fig. 2.3 reproduced and adapted from the NASA Earth Observatory website [58] provides a visual comparison for before and after the blackout caused by Hurricane Sandy.

Ignoring areas that are covered by cloud (labelled and bordered in white), the impact of the blackout can be seen by the relative brightness of both images before (top) and after (bottom) Hurricane Sandy’s landfall on 29th October 2012 and by the comparing the areas around the lines drawn in red and labelled A, B and C. The red dotted line labelled A has a far brighter area below it before versus after Sandy’s landfall. The area circled by the red line labelled B is particularly dark after Sandy’s landfall meanwhile the shape of upper Delaware Bay outlined by C shows that the coastline appears to be experiencing a complete blackout for about 5 km either side of it.

There are concerns that storms like ‘Superstorm Sandy’ that struck the east coast of North America in late October 2012 could become more common as the climate continues to change [59]. CO_2 (Carbon dioxide) is considered to be the primary GHG simply because of its sheer abundance in relation to more potent GHG in Earth’s atmosphere, but it is also the GHG released in the largest volumes by anthropogenic activities:

> *“CO_2 emissions have grown between 1970 and 2004 by about 80% (28% between 1990 and 2004) and represented 77% of total anthropogenic GHG emissions in 2004.”*
>
> - Intergovernmental Panel on Climate Change (IPCC), 2007 in [60].

Other chemicals constitute GHGs too [61]. Water vapour, for example, is one example and it is by far the most abundant GHG [14] and there are natural sources of GHGs that also need to be considered. The matter is further complicated by the existence of relationships between other GHG emissions and fossil fuels. Natural gas is predominantly constituted of CH_4 (Methane) which is itself a GHG and has a higher global warming potential than CO_2 [62], meaning that when deposits are found, burning natural gas may technically be better for the environment than allowing it to seep out naturally into the atmosphere. NO_x, are another group of emissions that like water vapour have natural sources, but are also produced by combustion processes including during electricity generation and use of internal combustion engines by road vehicles [14, 56].

Energy use of fossil fuels is a major contributor to GHG globally. Electricity generation and road transport were cited as being the largest contributors to increasing GHG emissions worldwide in 2004 and in terms of total global emissions for 2004 electricity generation was responsible for by far the highest GHG emissions [60]. Fossil fuels use is not the only source of GHG emissions. Land-use change accounts for roughly 18% of GHG emissions but these emissions originate from only a few countries [26]. In those countries land-use change can contribute large emissions of GHG to the atmosphere and not all of those being CO_2 [63].

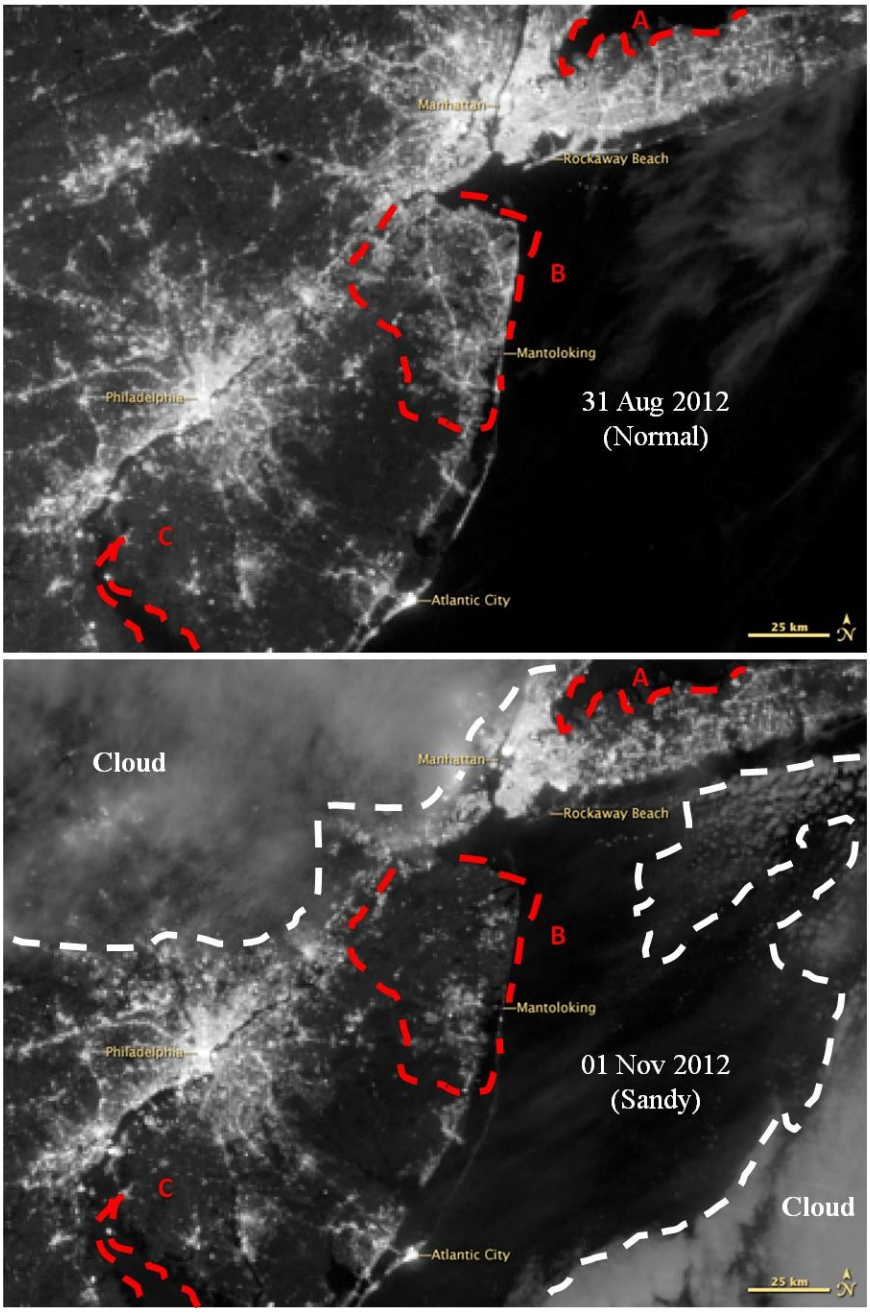

Fig. 2.3. Adapted night-time views of New York City, New Jersey and eastern Pennsylvania before (top) and after (bottom) Hurricane Sandy's landfall on 29th October 2012. Image credit: NASA Earth Observatory image by Jesse Allen and Rob Simmon, using VIIRS Day-Night Band data provided by Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin [58].

Many GHGs have both natural and anthropogenic sources, but natural processes that add or subtract GHGs from the atmosphere can be affected by anthropogenic activities too. Deforestation interrupts or reduces natural carbon sequestration and even if a forest is replaced with other plant species, the change can bring about a net loss in stored carbon [64]. Debate continues over whether or not anthropogenic emission of GHGs can promote the acceleration of some natural processes that release GHGs [65]. As the sun continues to undergo an unusually long period of reduced activity, it is hoped that this will make easier the task of better detecting changes in global temperatures from anthropogenic release of GHGs [66].

Such is the concern for GHG emissions that many nations have repeatedly declared intent to curb emissions of these gases. The UK government set targets for cutting its GHG emissions in 2007 [27]. As noted earlier, land-use chance can be a contributor but for the UK, land-use change in the UK in 2007 actually contributed a negative balance in emissions [67] and instead it is the energy use of fossil fuels that is the major source of GHG emissions for the UK [27], although non-energy use of fossil fuels can also contribute to GHG emissions [14, 19]. In 2008 CO_2 represented 85% of the UK's man-made GHG emissions [68], making it the UK's primary target for reducing GHG emissions.

2.4 SUMMARY: BRING THE UK FOCUS BACK TO FOSSIL FUELS

As can be noted from the sample of references mentioned so far, GHG emissions are typically the focus of researchers concerned with global scales of environmental impact arising from fossil fuel use. Other emissions associated with fossil fuel use feature in research focused at the more local, human health related scale. At both scales, energy use of fossil fuels in particular carries the weight of concern for negative impacts. Meanwhile governments addressing the energy security of their nations, might in truth consider energy security to be their greatest concern, related to their energy portfolio and the state of availability of those resources relative to their nation's needs both present and future.

All are valid reasons for interest in different areas, but when considered separately the overall interrelated core factor is ignored: fossil fuel use itself. Worse, they undervalue its necessity for modern living from healthcare to the provision of food, because compared to energy use, non-energy use of fossil fuels appears insignificant. Therefore below are listed the eight reasons drawn from this chapter as to why reduced use of fossil fuels, with special priority on energy use, particularly of petroleum products, should be the focus of present day research, in the UK:

1) Modern civilisation depends on the non-energy use of fossil fuels – particularly petroleum products – for modern healthcare, modern technology and to enable a workforce that is not solely devoted to the provision of their own food[4].
2) Native production of fossil fuels, specifically oil (the raw form of petroleum products) and gas, is expected to decline over the next decade [27]. The UK

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[4] Hygienic long distance transport of food wrapped in plastics, from where it is grown en masse by a small group of people to where it is eaten by a very large number of people, supports the existence of cities.

will therefore become increasingly dependent on imports of fossil fuels for both energy and non-energy uses. Non-energy use of fossil fuels, particularly petroleum, is relatively small compared to energy-use, so the UK could remain self-sufficient for longer if native reserves are conserved and used for non-energy purposes only.

3) Imports of fossil fuels cross many borders, making them vulnerable to stoppages in supply (by accident or incident) [27]. A delivery chain is only as strong as its weakest link: the longer the chain, the more links, the greater the potential to go wrong and the harder contingency planning becomes.
4) Most imports of fossil fuels originate from increasingly politically unstable areas of the world [27], making the UK's future energy security even harder to protect and compounding the risks associated with having to rely upon a long delivery chain.
5) The threat of lock-in to an alternative energy technology that is ecologically hazardous or economically unviable in the future as fossil fuel reserves become scarce in future (present rate of use far outstrips present rate of natural production processes) [28].
6) The threat of social crisis resulting from the incompatibility of present social institutions and a new energy technology when fossil fuel resources become scarce in the future [28].
7) The threat of rent-seeking oil wars to control dwindling petroleum reserves, as petroleum products in particular are the most important fossil fuel for the continuation of modern society (specifically: non-energy use) [28].
8) The UK government has agreed to set targets for cutting its GHG emissions [27], which in the UK arise primarily from the use of fossil fuels, but air quality impacts on health from emissions arising from the energy use of fossil fuels – particularly by transport – are also a key concern. They are a key concern because in the UK, public healthcare is paid for by taxes and provided by a nationalised health service (the NHS), preventing the economic externalisation of this particular environmental cost – the cost is covered by the state and is thus the debt is paid, instead of being passed onto stakeholders (e.g. the poor, or the disabled) that cannot themselves pay for it.

Other nations may have a different balance in their focus and it may be that fossil fuel use is a lesser concern for some nations than others, but for the UK all evidence points to a very strong dependency on fossil fuels and energy use of them being the root cause of a number of high priority problems. It is with the above listed reasons in mind that the next chapters will look at energy use in the UK to identify the biggest energy uses/users, considering also where the most fossil fuel is used and why and whether or not a shift in energy pathway dependency could bring about a decrease in overall fossil fuel consumption.

CHAPTER 3: ENERGY PATHWAYS

An energy pathway – the flow of energy from source to end use – has many interchangeable parts. A complete review of UK energy pathways is not the object of this study. This chapter will start first with a brief overview of alternative energy pathways exploring their innate complexity. Following this, the chapter will focus upon identifying key users and uses of energy in the UK in an attempt to identify key areas to target for change.

3.1 ALTERNATIVE ENERGY PATHWAYS

Weighing up an alternative energy pathway can be complicated by a number of things. There could be potential conflicts of interest with regards to how a resource is used, there may be arguments over which is the more efficient pathway for resource use. Such arguments may further be complicated by the relative increase or decrease of negative consequences when switching between specific alternative end-uses of a resource. These factors are interrelated and often overlap, however for ease of reading this part of Chapter 3 is roughly divided into three themes for considering alternative energy pathways: potential conflicts of interest, effective use of resources, and reducing negative impacts.

3.1.1 POTENTIAL CONFLICTS OF INTEREST

Energy is used by a wide variety of people for a wide variety of purposes in a wide variety of ways and what is more, some forms of energy have non-energy uses as well. The potential for conflicts of interest to occur is vast. As an opening example consider the prospect of Hydrogen (H_2) as an alternative energy pathway for transport. There are proposals for H_2 energy pathway – in particular a 'Hydrogen Highway' – which would introduce transport as a new and potentially large user of H_2 gas [69]. There is already a market for H_2 and it is dominated by demand for two non-energy purposes: to make agricultural fertilisers and in cracking to refine heavier fraction petroleum products into lighter ones more commonly used as fuels [70-72]. Switching road transport to H_2 dependency would make road transport a competitor for H_2 potentially against food production, especially if more H_2 would be used in transport than would be saved by reducing the demand for refined fuel.

Another example of conflicting interests would be land-use. Biofuels also often constitute species of crops that are otherwise used as food for people and animals and competition for land-use will limit the native production of biofuels in the UK, in particular: competition between food production and transport grade biofuels [73, 74]. Scale can also be a problem when it comes to matching cultivation to the size of demand. In 2006 the proportion of food demand met by local production fell to just 56% [75]. The possibility of environmentally-detrimental land-use changes made abroad in order to produce transport-grade biofuel for export to developed nations, has forced a government policy shift away from the substitution of fossil fuel with biofuel for transport according to the United Kingdom Renewable Energy Strategy (UKRES) report by the DECC [4].

Other factors can influence choice of energy pathway. Renewable alternatives for energy pathways are not immune to potential conflicts of interest, especially when deployed on large scales. In the Greek Aegean islands there is concern that large-scale renewable energy sources projects e.g. to take advantage of geothermal fields in Milos, could jeopardise the tourist character of the island [76]. For marine renewable energy devices for example, the laying of cables and anchoring of infrastructure to the seabed can disturb sediments and lead to habitat destruction, with knock-on effects on shipping patterns potentially leading to impacts upon marine flora and fauna elsewhere [77]. The prime motive for pursuing renewable resources is usually to reduce environmental degradation, so if switching to renewable resources is a bad thing for the environment the argument for change is undone.

Conflicts of interest are not always a bad thing: the sooner they are considered the better the success of efforts to resolve them and the more sustainable a proposal will be. In the example of marine renewables the UK government has, since concerns were raised for environmental damage, put in place a statutory decommissioning regime as part of their framework for offshore renewables in an attempt to ensure that funds set aside for decommissioning are secure for that purpose in the event of insolvency [27]. Hopefully this will at least safeguard marine environments from the dangers of improper decommissioning.

3.1.2 EFFECTIVE USE OF RESOURCES

Why, where and how a resource is used is as important as considering a switch from use of one resource to an alternative. Biofuels have a similar chemical composition to fossil fuels, and like fossil fuels they have energy and non-energy use pathways that they could be assigned to: they can be burned as fuel or for example processed as an alternative feedstock for H_2 production [78-80]. Given that H_2 is at present predominantly derived from fossil fuel feedstock [78, 81], one could argue therefore that it would be better to derive H_2 from biofuel than from fossil fuels.

Unfortunately as noted previously: a primary destination of H_2 is the production of agricultural fertilisers [70-72]. In other words: biofuel production can be indirectly dependent upon fossil fuels through the use of inorganic nitrogen-based fertilisers. This can account for up to 37% of the fossil fuel energy input to biofuel production [73]. If the purpose of biofuels were to become production of H_2 then the question would need to be asked: can more H_2 come out of this cycle than gets put into it and will it lead to an overall reduction in fossil fuel dependency?

Applications of biofuel might also be better determined by considering the circumstances in which biofuels are grown. The UK is historically ideal both in soil and climate for the support of large forests and scrublands [82, 83]; the sorts of conditions better suited for heat and power grade biofuels. Depending on the feedstock in question (thus different land-use, climate and processing requirements), biofuels may be better suited for energy use for heat and power than for transport, at least in the UK [73, 84, 85].

Adding weight to the argument for heat and power grade transport fuels to be grown in the UK: when transport grade biofuels (for use in existing types of internal combustion engine vehicles) have all the best conditions, the end product is still inferior to fossil fuels when considering compound efficiencies [6]. A comparison made of calorific values for fossil transport fuels reported in [14] and calorific values of biodiesel and bioethanol as described by [86] suggest biofuels are inferior to fossil fuels in this respect too. Lastly, the growth of some biofuels can be combined with phytoremediation (environmental clean-up using plants) techniques that could help make UK biofuels more economical [73]. Testing is particularly well-documented for phytoremediation coupled with energy crop cultivation for several Short Rotation Coppice (SRC) tree species used to produce heat and power grade biofuels, and although other energy crops have not been investigated, it seems unlikely that others could be as multifunctional as these [73].

The electricity pathway is a good example for considering the effective use of energy because of its complexity: it has variable starting points, with a mix of resources contributing, each with potential to contribute towards generation by varying degrees. UKRES [4] suggests that up to 30% of UK electricity generation could be sourced renewably by 2020, however even renewable energy resources can have alternative uses and thus alternative pathways. Solar energy is a good example: it can be directed towards electricity production through photovoltaic cells, but it is also suitable for heat generation through solar thermal units [87] and in a list of H_2 production methods, Navarro et al. [78] note that amongst them that the use of solar energy is the most promising. H_2 is at present predominantly derived from fossil fuel feedstock [78, 81] so renewable alternatives for supply are of great interest, but Navarro et al. [78] admit much work must be done before H_2 can be produced renewably from any of the options they listed on a commercial scale.

As noted previously, electricity is an excellent energy carrier that can be converted into heat, light, sound, kinetic (motor) and chemical energy (batteries) [6] meaning it has become the primary energy pathway for a variety of energy end-uses. There is however a question of relative efficiency for specific purposes of use. Efficiencies in the UK for thermal conversion of fuel by generators into electricity averaged 36.0% for coal, 51.9% for gas and 37.9% for nuclear in the year 2007 [14]. The efficiency of conversion of fuels to heat on the other hand can be far higher: natural gas can be converted to useful thermal energy in a modern condensing boiler at efficiencies upwards of 90% [27]. It is therefore more energy efficient to burn fossil fuels to produce heat than to convert them into electricity and then subsequently into heat [6, 88]. Electricity generation can however be coupled with heat generation for greater combined energy efficiency [6, 27]. In the UK, co-generation or combined heat and power (CHP) is boasted by the Combined Heat and Power Association (CHPA) to have overall efficiencies of 80% or higher for conversions to energy that will subsequently be used [89], meanwhile:

> *"The energy savings delivered by CHP are underpinned in law and through supporting regulations. The EU Cogeneration Directive defines CHP as delivering minimum levels of primary energy savings, with savings of 10% required for most CHP capacity. This legal requirement, which must be met to qualify for most forms of public support, is enacted in the UK through the CHP Quality Assurance (CHPQA) programme. Energy savings secured are however typically often far greater than this minimum threshold."*
>
> - CHPA, from [90]

What to use for which purpose is not the only question affecting the effective use of resources: the location of resources relative to demand adds another dimension for consideration. Distributed electricity generation for example can help energy security in some (typically rural) areas, whilst taking advantage of local energy resources [91] and potentially reducing environmental and other impacts by minimising the scale of individual installations [76]. In [92] it is suggested that wind microgeneration, if located sensibly, might potentially provide significant and predictable power dispatch to household dwellings.

Distributed generation can also be used to turn a problematic waste substance produced locally into a useful resource. Pig effluent when in large volumes and concentrations contributes to water pollution, but it can also be used to provide methane for electricity generation while the remaining by-products can be converted into fertiliser which can substitute artificial (fossil fuel derived) fertilisers [93]. Self-sufficiency can be socially attractive enough to appeal for fundraising efforts to be made to aid implementation, as exampled when Limpley Stoke village asked residents whether a 500 MW hydroelectric generator would be a project of interest to the community [94]. Homeowners across the UK meanwhile have been enticed by the prospect of Feed In Tariffs (FIT) that will reward them for using renewable energy generation and allow them to sell any surplus electricity to their electricity suppliers [4].

3.1.3 REDUCING NEGATIVE IMPACTS

As noted in the introduction: non-energy use of fossil fuels is integral to modern civilisation meanwhile fossil fuels are a finite resource when rate of use versus rate of production is considered. A range of negative impacts accompany energy use of fossil fuels meanwhile energy use of fossil fuels is the main end-purpose of fossil fuel use in the UK. For this reason technology such as CHP is not only appealing for its potential gains in fuel efficiency as noted previously but also for its potential reduction of negative impacts related to energy use of fossil fuels. In the DECC's webpage for CHP [95] for example it is stated that CHP can reduce carbon emissions by up to 30%, compared to getting heat and power separately via a boiler and power station.

Road transport is recognised internationally as a primary contributor to atmospheric pollution (both local and global) and as a primary user of energy, particularly of fossil fuels. According to the 2010 World Energy Outlook report produced by the IEA [96], in the year 2009 around 96% of energy used by road transportation was oil-based fuels, meanwhile transport's share in global primary oil consumption was 53%. As a sector road transport has many energy pathways open to it but it is dominated by the internal combustion engine vehicle (ICEV). UK road transport is predominantly dependent upon motor spirit (petrol) and DERV (diesel) [5].

There have been many alternatives cited over the years, including permanently grid-connected vehicles [97], pure Battery Electric Vehicles (BEV) such as the Nissan Leaf [98] and flexi-fuel vehicles (FFVs) such as the Saab 9-5 BioPower [99] which can use fuels with a higher mix of biofuel such as the E85 mix. These may potentially overlap with other alternative forms of transport including those that combust Compressed Natural Gas (CNG) and those that use fuel cells for which there are biofuel options, as well as H_2 gas [100-102].

There has been much interest over the past few years in the prospect of introducing a H_2 energy pathway, especially for transport. The intermittency of many types of renewable electricity generation promotes the need for storage of electricity generated during off-peak periods. H_2 has been suggested as a possible clean storage medium for this purpose [103, 104] in that it could be co-produced during electricity generation, then used as a fuel for vehicles (via combustion or fuel cell), or stored and later used for electricity generation. End-use of H_2 is however still under debate, as are its sources.

Fuel cells offer the better improvement in emissions because when combusted H_2 too generates emissions – namely NO_x. Due to the high temperatures associated with H_2 combustion, more NO_x may potentially be generated through H_2 combustion than through the combustion of other fuels [81, 105]. Unfortunately while H_2 is predominantly derived from fossil fuel feedstock not renewable sources [78, 81], this raises concerns regarding pathway efficiency if the purpose of switching to H_2 energy pathway is to reduce fossil fuel consumption. Even so, if the purpose of end-use is transport (and especially if renewable production of H_2 is possible) then H_2 might be the preferable energy pathway when compared against electricity. Thomas [106] argues that it is more energy efficient to convert natural gas to H_2 for use by road transport in fuel cells than to convert it into electricity to recharge the batteries of electric vehicles and that well-to-wheel emissions are lowest for fuel cell electric vehicles (FCEV) but no comparison was made between these two pathways and the petroleum products pathway.

Hybrid road vehicles are another frequent point of interest that comprise a variety of technologies with sometimes complicated reliance on a mixture of energy pathways. Gurkaynak and Khaligh [107] describes combining balancing electricity generation from home-fixed solar panels with mains electricity for recharging a plug-in hybrid electric vehicle (PHEV) that also can rely upon fuel for energy needs, making the vehicle have no less than three ways to source its energy. If biofuel makes up a portion of a hybrid's generalist energy consumption, then the energy pathways used by that vehicle could be even more complex.

Energy use of biofuels however can produce unwanted emissions in a similar way to that of the energy use of fossil fuels. GHG become less important because ideally biofuels should be Carbon neutral (Carbon released should equal Carbon sequestrated from the atmosphere by the biofuels when they were being grown) but there are still other pollutants produced. Aldehyde emissions are higher for the combustion of bioethanol than for fossil fuel alternatives [108] and ultrafine particulate matter emissions are higher for vehicles that use biodiesel and bioethanol than fossil fuel equivalents [109]. Biogas derived from wood, typically classed as a heat and power grade biofuel, is proposed as another alternative fuel for transport by [100] for the UK although as with H_2 it is noted that a supply network for transport may need to be built from scratch. Biogas as a transport fuel may produce upon combustion lower emissions of CO_2, CO, NO_x and ultrafine particulate matter than biodiesel and bioethanol [101].

In summary there are a variety of energy pathways in use in the UK, requiring varying degrees of effort to bring about a switch from one energy pathway to another and a host of varying positive and negative consequences. Caution is required when proposing one approach is better than any other. The next part of this chapter will show what the largest energy uses are to which users these uses are attributed, and so elucidate the primary energy pathways in use for the UK.

3.1.4 ELECTRICITY AS AN ALTERNATIVE ENERGY PATHWAY

Many energy pathways start and end in roughly the same form of energy e.g. primary oils, which are refined into petroleum products, which are then both storage and transmission mediums for energy to final users. Electricity however, is neither a source nor necessarily the last form of energy prior to conversion in end use, but as a transmission medium it is unparalleled for the following reasons:

- **Versatility of end-use** – electricity can easily be converted into several other forms of energy including light, heat, sound and kinetic and there is well-established technology for each conversion.
- **Clean at point-of-use** – other energy carriers are well-known for creating unwanted by-products that degrade either the environment, human health, or both during conversion to end-use forms of energy. Electricity use avoids nearly all of these.
- **Efficiency of conversion** – electricity can be converted to several other forms of energy with very little in the way of lost or wasted energy compared with other energy carriers.
- **Versatility of supply** – electricity can be derived from a variety of resources, including unsustainable resources such as fossil fuels and nuclear but also a range of renewable resources such as sunlight, wind and the motions of bodies of water (e.g. falling from a dam or shifting tides).
- **Electricity transportation and distribution** – losses from transmission and distribution of electricity may be higher or comparable to those for the transportation of fuels but there are less environmental consequences when electricity is ‘spilled’ compared to fuels. Also when a fault occurs in an electricity transmission and distribution system, there are no lorries loaded with electricity getting stuck in traffic, being backlogged and prevented from timely arrival at their destination: instead as soon as the fault is fixed the electricity is almost instantly available again to the end-user. Lastly, electricity infrastructure (at least when compared to fuel tankers for example) is exposed to a lesser variety of supply-halting risks, less frequently.
- **Pathway already in use** – electricity is already in use in the UK with an expansive distribution network already in place and a multitude of applications already in use and commonly accepted by the public.

This is not to say that electricity-based energy pathways are the only kind available, nor are electricity-based pathways necessarily the best choice, particularly at local scales if environmentally friendly alternatives are in abundance. Logic dictates that the number of energy conversions in an energy pathway should be minimised to facilitate maximum energy efficiency so where there are possibilities for biofuel that provide ecosystem or environmental clean-up services, biofuel should be used. Where there is an abundance of heat from the sun, this can be combined with collectors, concentrators and storage to provide heat after dusk.

Electricity is, however, an extremely useful tool for facilitating balance between energy demands and supply at larger scales, and as a transition tool for switching between other alternatives. Through its versatility both in terms of supply and end-use, electricity lends itself toward being easily adopted as a replacement for other energy pathways and makes it possible to introduce changes to both ends – sources and uses – of a supply system simultaneously. This means that even where electricity supply is presently dependent upon fossil fuels, it is possible it does not have to remain so and may not be in future.

Electricity's biggest value is in the way it shapes detrimental impacts from energy use by being clean at point-of-use and by shifting the responsibility for placement of mitigation measures away from prolific, widely dispersed individuals (number and distribution make regulation of mitigation measures difficult) and towards a few, centralised authorities who can be regulated more effectively.

3.2 TOP ENERGY USE/USER GROUPS IN THE UK

In 2007 the main fuels used by final consumers according to [3] were: petroleum products (48%), natural gas (31%) and electricity (18%). In 2011 little had changed except a slight shift in shares to 48% for petroleum products, 29% for natural gas and 19% for electricity [12]. This proves the heavy dependence upon fossil fuels for the UK, but as for targeting points for changing dependency from one form of energy to another, a closer look is required.

Other types of investigative techniques for UK energy usage have focused on exergy[5] analysis of the UK's energy system over the course of 30 years [110] or exergy together with emergy synthesis[6] [111, 112] in the context of sustainability. Unfortunately these techniques involve far more detail than will be investigated here and definitions of emergy and exergy do not appear to be in common use. The DUKES report for 2008 [3] provided flow charts for different 'fuels' under Annex H, but does not show similar diagrams for energy pathways and arguably an energy pathway diagram for the whole of energy use in the UK would be incredibly complicated to create.

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[5] "The thermodynamic property exergy (also known as availability) shows how far a device is operating from its thermodynamic ideal, allowing all energy conversion devices to be compared on an equivalent basis." according to [6]. In the same reference, exergy efficiency is calculated by multiplying the energy efficiency of a given conversion by a quality factor.

[6] In [111] Emergy Synthesis – EmS – "essentially quantifies the environmental support required to produce all the inputs that are consumed by the society while the total emergy consumed is an indication of its total appropriation of environmental services."

A ranking method is therefore introduced in this part of Chapter 3, the goal of which is not to judge sustainability but to find key areas of interest only. Key use/user group(s) will be identified by analysing the 2008 DUKES Aggregate Energy Balance table for 2007 [3][7]. If a large segment of energy is being used in the same way by the same sort of technology, then logically this may indicate a good target for change. If a large segment of energy is derived or transported in the same way, again the same applies. Points on an energy pathway that will be difficult to modify are those outside of state legal or regulatory influence (only limited reference to that influence is made here) and all the points where there is vast diversity in provision or use, indicating a large amount of variety in the motivations for use and technology used.

3.2.1 GENERAL EXPLANATORY NOTES

For ease of reference, the Aggregate Energy Balance (henceforth shortened to AEB) table for 2007 from the 2008 DUKES report [3] was reproduced as part of Fig. 3.1. It will be referred to and used extensively for much of the remainder of this chapter in identifying key energy use/user groups and in comparing key energy pathways in Chapter 4. There are, however, definitions that apply to terms used in the table. Firstly it should be noted that the report [3] considers energy usage in terms of primary and secondary *fuels*. A summary of the definitions from the report is provided here as these terms will be used throughout the remainder of this chapter. *Primary fuels* include:

- *coal*
- *primary oils*
- *natural gas*
- *nuclear electricity*
- *natural flow hydro-electricity*, which does not include electricity generated from pumped storage
- *renewable energy sources*, which in the table is combined with energy use from waste including both biodegradable and non-biodegradable (e.g. landfill gas)

In the AEB table from [3] reproduced as part of Fig. 3.1 therefore *primary electricity* is defined as electricity generated by *nuclear* and *natural flow hydro*. In the report [3] *secondary fuels* are then listed as including:

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[7] Note that more up-to-date figures for the table can be found in the 2012 edition of the DUKES report [12], but at the time the work was conducted, the 2008 edition [3] was the latest edition available.

- *manufactured fuel* – e.g. coke, blast furnace gas
- *petroleum products* – which are transformed from *primary oils* hence being a secondary fuel
- *secondary electricity* - this is electricity generated from the combustion of primary fuels including fossil and renewable kinds
- *heat* – specifically heat produced and sold under the provision of a contract

In the AEB table from the report [3] reproduced as part of Fig. 3.1 it should be noted that the *Electricity* column is actually the sum of both *primary* and *secondary electricity* delivered to consumers. The figure for electricity generated through *transformation* processes (32,865 ktoe), minus *losses* in transmission and distribution (2270 ktoe) and the electricity generation industry’s own use of electricity (1555 ktoe), plus net imports (449 ktoe), roughly equals the amount of electricity totalled under ‘final consumption’ of electricity by other sectors, but not exactly. At national scales, balancing figures exactly – for example supply versus demand of electricity – can be very difficult. There are errors in reporting and data collection that can mean there are discrepancies in the AEB table from [3] and as such the calculations performed in this chapter and the next, based upon these figures, should be treated as being rough estimates useful for grasping only the general big picture of energy usage in the UK.

The *transfers* row of the AEB table [3] reproduced in Fig. 3.1 covers incidents where one commodity may have been reclassified as another for various reasons prior to use of any kind, hence the positioning of the row above the *transformation* section of the AEB table. There are several reasons why quantities may be transferred from one commodity column to another:

> *“A commodity may no longer meet the original specification and be reclassified, the name of the commodity may change through a change in use, or to show quantities returned to supply from consumers. These may be by-products of the use of commodities as raw materials rather than fuels.”*
>
> - BERR (in reform), from paragraph A.15 in [3]

During oil and gas extraction for example, there is usually a fraction of primary oils that need little or no transformation, so in the AEB table it can be seen that this fraction is moved from the *primary oils* column to *petroleum products* column and that as this was a change in name only, there are no losses. Another example is electricity where *primary electricity* sourced from renewables is transferred directly to the *electricity* column i.e. electricity supplied. The *transfers* row in all the AEB tables of the report [3] should ideally sum to zero. The *transfers* row does not affect figures for end-use of energy (recorded separately in other sections of the AEB tables) but only affects the naming of the commodities being input.

Finally, please note that in this chapter and the next, all work and calculations were performed in Microsoft Excel 2007. The AEB table in [3] was copied into a spreadsheet and different tabs within that spreadsheet were then used to carry out the methods described in this chapter for establishing key use/user groups in this chapter and for comparing energy pathways in the next chapter. Notes were made wherever applicable within the spreadsheet to include quotes and references to the original source document when relevant. Original figures unchanged from the AEB table in [3] were formatted in **black** font colour on the spreadsheet. Figures altered by calculation or combination processes as part of the methods documented in this chapter were formatted in **purple** font colour. This is evidenced by all screenshots of Excel work included in this chapter and was helpful in keeping track of changes.

3.2.2 DETERMINING USE/USER GROUPS – AEB RECALCULATION METHOD

The focus of this method is to establish end-use of energy, wherever it may be, including (where in concerns energy industry use) wasted energy as a type of energy use – the point being that energy wasted in transformation plus any energy the industry uses (e.g. to maintain lighting and heating in their offices) is "energy used to get the job done."

The AEB table from [3] unfortunately could not be taken at face value because initially it separates all energy use for transformation purposes from final consumption, so entries had to be restructured and energy use for subsequent energy use/user groups recalculated.

Fig. 3.1 summarises steps 1 through 5 of the process that was used to disassemble the contents of the AEB table from [3] (reproduced in miniature as part of Fig. 3.1) and reintegrate them into new use/user groups ready for ranking. Fig. 3.2 displays the new use/user groups prior to ranking, concluding step 5, and summarises step 6. The two foldout A3 sheets displaying Fig. 3.1 and Fig. 3.2 thus summarise the process of determining use/user groups and ranking them. Additional explanatory notes about each the steps involved are provided to accompany the figures.

3.2.2.1 Step 1 – Adjust for transformations (notes)

As noted in Fig. 3.1, this step calculates net energy usage (losses) for *transformation*. This is part of the energy that arguably "it took to get the job done" – the job of the end-users (in this section: the energy industries themselves) being to provide energy to other end-users (their customers) and all their energy usage is towards that purpose. Energy outputs from *transformation* are therefore subtracted so that energy use by end-users is attributed to end-users only. It is assumed at this point in the energy use/user grouping process that all transformed energy was delivered to other end-users (customers of the energy industries), whose energy use is documented in the lower section of the AEB table [3] reproduced in Fig. 3.1. Energy in the *transfers* row is assumed to sum to zero therefore is not included.

It would defy the laws of physics to get more energy out of *transformation* processes than was put in, but this appears initially to be the case for *petroleum refineries* and *patent fuel manufacture*. The report from whence the AEB table comes [3] notes that there are sometimes discrepancies and errors in the information collected or in the ways that energy is measured or converted into common units. Negative net energy use figures were thus corrected to zero and those *transformation* processes where this applied simply assumed to have negligible losses.

3.2.2.2 Step 2 – Energy industry own use of energy (notes)

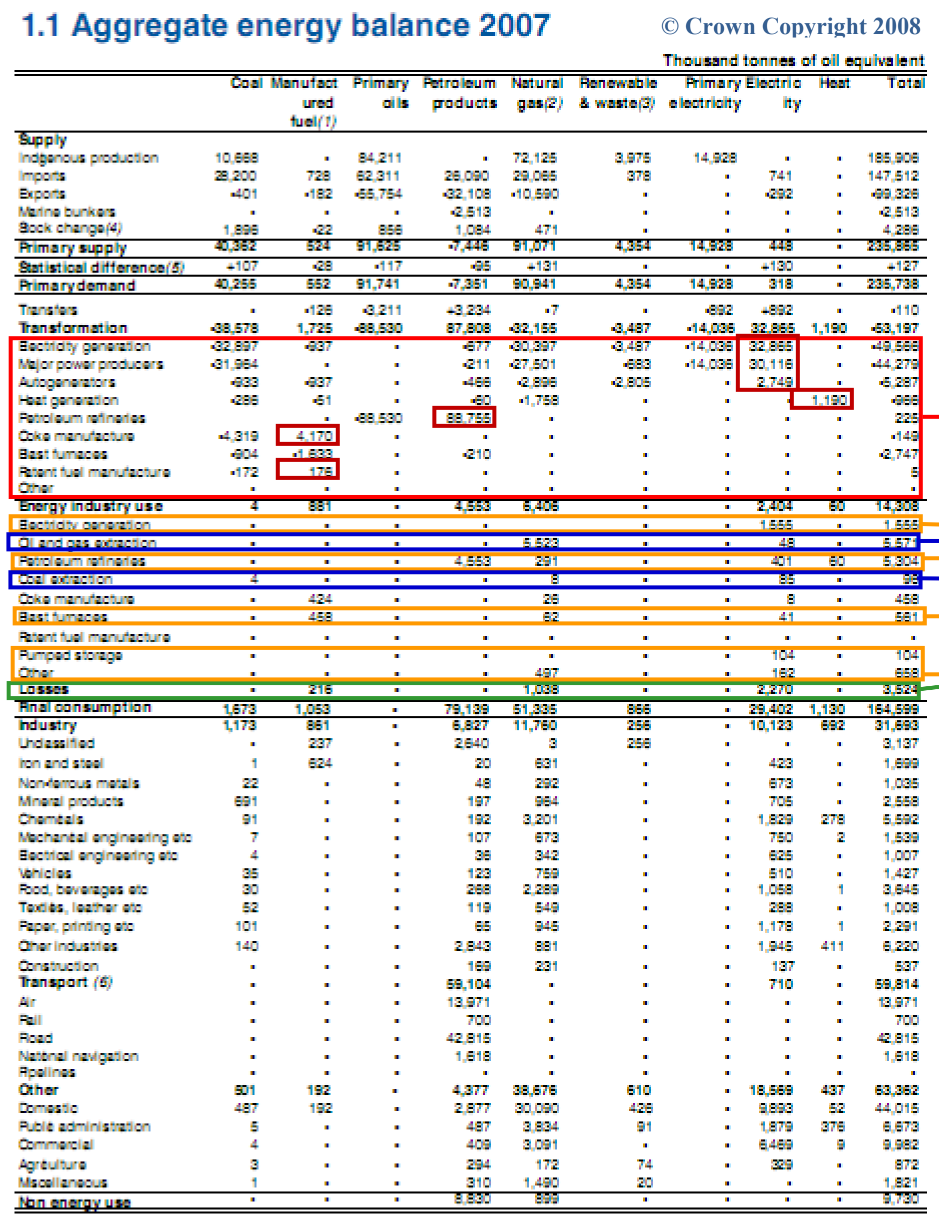
In this step (as noted in Fig. 3.1) *transformation* processes and *energy industry use* sections of the AEB table [3] are merged so that energy use listed under matching headings falls under one group e.g. *transformation* losses from *electricity generation* and *energy industry use* for *electricity generation* now fall under one group: *electricity industry*. Next, the *losses* recorded for different energy industries must be handled, and these are tackled in Step 3 whilst energy used in extraction of resources is covered Step 4.

3.2.2.3 Step 3 – Attributing losses (notes)

As noted by Fig. 3.1, *losses* listed under *energy industry use* are redistributed to the energy industries that incurred them, proportional to the amount of energy each used of the fuel that was lost. Correspondence with James Hemingway at the Department for Environment and Climate Change (DECC) confirmed that for the *losses* row in the AEB table [3], *losses* under *electricity* were solely attributed to the electricity generation industry, specifically as regards to transmission and distribution.

The remaining losses under *manufactured fuel* (216 ktoe) and *natural gas* (1038 ktoe) were redistributed to energy industry users of *manufactured fuel* and *natural gas*. Example of this is given in Fig. 3.1. for losses of *natural gas*, so for instance as *electricity generation* was responsible for 86% of *natural gas* used by the energy industry for non-transformation processes, 86% of the figure for natural gas losses was added to the *electricity industry*'s total figure during reintegration. Here as before, losses are classed as an energy use by energy industries on the principle that energy going into energy industries but not subsequently used by their customers should be considered part of the process of "getting the job done" for delivering those customers their energy.

Fig. 3.1. Summary of steps 1 to 5: determining top energy use/user groups, using data from '1.1 Aggregate energy balance 2007', reproduced in this figure from [3].



1.1 Aggregate energy balance 2007

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Thousand tonnes of oil equivalent

	Coal	Manufactured fuel(1)	Primary oils	Petroleum products	Natural gas(2)	Renewable & waste(3)	Primary electricity	Electricity	Heat	Total
Supply										
Indigenous production	10,668	-	84,211	-	72,125	3,975	14,928	-	-	185,906
Imports	28,200	728	62,311	26,090	29,065	378	-	741	-	147,512
Exports	-401	-182	-55,754	-32,108	-10,590	-	-	-292	-	-99,326
Marine bunkers	-	-	-	-2,513	-	-	-	-	-	-2,513
Stock change(4)	1,896	-22	856	1,084	471	-	-	-	-	4,286
Primary supply	40,362	524	91,625	-7,446	91,071	4,354	14,928	448	-	235,865
Statistical difference(5)	+107	-28	+117	-95	+131	-	-	+130	-	+127
Primary demand	40,255	552	91,741	-7,351	90,941	4,354	14,928	318	-	235,738
Transfers	-	-126	-3,211	+3,234	-7	-	-692	+692	-	-110
Transformation	-38,578	1,725	-88,530	87,808	-32,155	-3,487	-14,036	32,865	1,190	-63,197
Electricity generation	-32,897	-937	-	-677	-30,397	-3,487	-14,036	32,865	-	-49,568
Major power producers	-31,964	-	-	-211	-27,501	-683	-14,036	30,116	-	-44,279
Autogenerators	-933	-937	-	-466	-2,896	-2,805	-	2,749	-	-5,287
Heat generation	-286	-61	-	-60	-1,758	-	-	-	1,190	-966
Petroleum refineries		-	-88,530	88,755	-	-	-	-	-	225
Coke manufacture	-4,319	4,170	-	-	-	-	-	-	-	-149
Blast furnaces	-904	-1,633	-	-210	-	-	-	-	-	-2,747
Patent fuel manufacture	-172	176	-	-	-	-	-	-	-	5
Other	-	-	-	-	-	-	-	-	-	-
Energy industry use	4	881	-	4,553	6,406	-	-	2,404	60	14,308
Electricity generation	-	-	-	-		-	-	1,555	-	1,555
Oil and gas extraction	-	-	-	-	5,523	-	-	48	-	5,571
Petroleum refineries	-	-	-	4,553	291	-	-	401	60	5,304
Coal extraction	4	-	-	-	8	-	-	85	-	98
Coke manufacture	-	424	-	-	26	-	-	8	-	458
Blast furnaces	-	458	-	-	62	-	-	41	-	561
Patent fuel manufacture	-	-	-	-	-	-	-	-	-	-
Pumped storage	-	-	-	-	-	-	-	104	-	104
Other	-	-	-	-	497	-	-	162	-	658
Losses	-	216	-	-	1,038	-	-	2,270	-	3,524
Final consumption	1,673	1,053	-	79,139	51,335	866	-	29,402	1,130	164,599
Industry	1,173	861	-	6,827	11,760	256	-	10,123	692	31,693
Unclassified	-	237	-	2,640	3	256	-	-	-	3,137
Iron and steel	1	624	-	20	631	-	-	423	-	1,699
Non-ferrous metals	22	-	-	48	292	-	-	673	-	1,035
Mineral products	691	-	-	197	964	-	-	705	-	2,558
Chemicals	91	-	-	192	3,201	-	-	1,829	278	5,592
Mechanical engineering etc	7	-	-	107	673	-	-	750	2	1,539
Electrical engineering etc	4	-	-	36	342	-	-	625	-	1,007
Vehicles	35	-	-	123	759	-	-	510	-	1,427
Food, beverages etc	30	-	-	268	2,289	-	-	1,058	1	3,645
Textiles, leather etc	52	-	-	119	549	-	-	288	-	1,008
Paper, printing etc	101	-	-	65	945	-	-	1,178	1	2,291
Other industries	140	-	-	2,843	881	-	-	1,945	411	6,220
Construction	-	-	-	169	231	-	-	137	-	537
Transport (6)	-	-	-	59,104	-	-	-	710	-	59,814
Air	-	-	-	13,971	-	-	-	-	-	13,971
Rail	-	-	-	700	-	-	-	-	-	700
Road	-	-	-	42,815	-	-	-	-	-	42,815
National navigation	-	-	-	1,618	-	-	-	-	-	1,618
Pipelines	-	-	-	-	-	-	-	-	-	-
Other	501	192	-	4,377	38,676	610	-	18,569	437	63,362
Domestic	487	192	-	2,877	30,090	426	-	9,893	52	44,015
Public administration	5	-	-	487	3,834	91	-	1,879	376	6,673
Commercial	4	-	-	409	3,091	-	-	6,469	9	9,982
Agriculture	3	-	-	294	172	74	-	329	-	872
Miscellaneous	1	-	-	310	1,490	20	-	-	-	1,821
Non energy use	-	-	-	8,830	899	-	-	-	-	9,730

Step 1 – Adjust for transformations

Reverse signs for figures so energy inputs become positive and energy outputs (highlighted in red) become negative, sum to give net energy used. Any minus net energy used figure corrected to zero. Transfers ignored and assumed to sum to zero.

Sample...

Transformation process	Total energy input (ktoe)	Net energy used (ktoe)
Electricity generation	82431	**49566**
Heat generation	2155	**965**
Petroleum refineries	88530	**-225**

Step 2 – Energy industry own use of energy

Match energy used by the energy industry classed as 'own use' to that listed under transformation.

Sample...

Group	Total Energy Used	
Electricity Industry		**54785**
(transformations)	*49567*	
(industry own use)	*1555*	

Step 3 – Attributing losses

Redistribute losses to the energy industries that incurred them, proportional to the amount of energy each used of the fuel that was lost.

Sample...

B) ACCOUNTING FOR NATURAL GAS LOSSES

Energy Industry Use	Natural gas used (ktoe)	Percentage of total natural gas used (%)	Energy attributed to natural gas losses in pipelines (ktoe)
Electricity generation	-	-	-
Oil and gas extraction	5,523	86	895
Petroleum refineries	291	5	47
Coal extraction	8	0	1
Coke manufacture	26	0	4
Blast furnaces	62	1	10
Patent fuel manufacture	-		
Pumped storage	-	-	-
Other	497	8	81
TOTAL	6,407	100	1038

Step 4 – Resource extraction

Redistribute energy used in extraction of energy resources to those energy industries that use them. Includes Primary oils transferred to Petroleum products.

Sample...

Users of Coal	Amount of coal (ktoe)	Amount of coal (ktoe)
Electricity generation	32897	80
Heat generation	286	1
Coke manufacture	4319	10
Blast furnaces	904	2
Patent fuel manufacture	172	0

Step 5 – Integrating groups

The final step is to integrate all the energy use as it has been attributed and redistributed to different groups to produce the final group list and then to rank by magnitude of energy use. The full integration list is provided overleaf in Fig. 3.2.

Sample...

Group	Total Energy Used	
Electricity Industry		**54692**
(transformations)	*49566*	
(industry own use)	*1555*	
(Pumped storage)	*104*	
(attributed losses in transmission and distribution of Electricity)	*2270*	
(attributed energy for the extraction of coal used)	*80*	
(attributed energy for the extraction of oil/gas used)	*1118*	

Step 5 – Cont.

Bold purple headings indicate newly defined use/user groups except for the "Transport Sector" whose groupings remained unchanged.

Step 6 – Rank and display

The next task was to rank these new use/user groups to determine where the most energy is used, by who and for what purposes.

	Group	Total Energy Used (ktoe)	
ENERGY INDUSTRIES	**Electricity industry**		**54692**
	(transformations)	*49566*	
	(industry own use)	*1555*	
	(Pumped storage)	*104*	
	(attributed losses in transmission and distribution of Electricity)	*2270*	
	(attributed energy for the extraction of coal used)	*80*	
	(attributed energy for the extraction of oil/gas used)	*1118*	
	Heat generation		**1030**
	(transformations)	*965*	
	(attributed energy for the extraction of coal used)	*1*	
	(attributed energy for the extraction of oil/gas used)	*65*	
	Petroleum refinery		**8725**
	(industry own use)	*5304*	
	(attributed losses in transmission and distribution of Natural gas)	*47*	
	(attributed energy for the extraction of oil/gas used)	*3374*	
	Coke manufacture		**726**
	(transformations)	*149*	
	(industry own use)	*458*	
	(attributed losses of manufactured fuel)	*104*	
	(attributed losses in transmission and distribution of Natural gas)	*4*	
	(attributed energy for the extraction of coal used)	*10*	
	(attributed energy for the extraction of oil/gas used)	*1*	
	Blast furnaces		**3435**
	(transformations)	*2747*	
	(industry own use)	*561*	
	(attributed losses of manufactured fuel)	*112*	
	(attributed losses in transmission and distribution of Natural gas)	*10*	
	(attributed energy for the extraction of coal used)	*2*	
	(attributed energy for the extraction of oil/gas used)	*2*	
	Other energy industry use		**757**
	(industry own use)	*658*	
	(attributed losses in transmission and distribution of Natural gas)	*81*	
	(attributed energy for the extraction of oil/gas used)	*18*	

OTHER "INDUSTRY"	**Unclassified industry use**		**3137**
	(industry use)	*3137*	
	Iron and steel industry use		**1722**
	(industry use)	*1,699*	
	(attributed energy for the extraction of oil/gas used)	*23*	
	Non ferrous metals industry use		**1046**
	(industry use)	*1035*	
	(attributed energy for the extraction of oil/gas used)	*11*	
	Mineral products industry use		**2595**
	(industry use)	*2558*	
	(attributed energy for the extraction of coal used)	*2*	
	(attributed energy for the extraction of oil/gas used)	*35*	
	Chemicals industry use		**5710**
	(industry use)	*5592*	
	(attributed energy for the extraction of oil/gas used)	*118*	
	Mechanical engineering etc. industry use		**1564**
	(industry use)	*1,539*	
	(attributed energy for the extraction of oil/gas used)	*25*	
	Electrical engineering etc. industry use		**1020**
	(industry use)	*1,007*	
	(attributed energy for the extraction of oil/gas used)	*13*	
	Vehicles industry use		**1455**
	(industry use)	*1,427*	
	(attributed energy for the extraction of oil/gas used)	*28*	
	Food, beverages etc. industry use		**3729**
	(industry use)	*3,645*	
	(attributed energy for the extraction of oil/gas used)	*84*	
	Textiles, leather etc. industry use		**1028**
	(industry use)	*1,008*	
	(attributed energy for the extraction of oil/gas used)	*20*	
	Paper, printing etc. industry use		**2326**
	(industry use)	*2,291*	
	(attributed energy for the extraction of oil/gas used)	*35*	
	Other industries		**6252**
	(industry use)	*6,220*	
	(attributed energy for the extraction of oil/gas used)	*32*	
	Construction industry use		**545**
	(industry use)	*537*	
	(attributed energy for the extraction of oil/gas used)	*8*	

"TRANSPORT"	**Air transport use**		**13971**
	(recorded use)	*13971*	
	Rail transport use		**700**
	(recorded use)	*700*	
	Road transport use		**42815**
	(recorded use)	*42815*	
	National navigation use		**1618**
	(recorded use)	*1618*	
"OTHER"	**Domestic use**		**45123**
	(recorded use)	*44015*	
	(attributed energy for the extraction of coal used)	*1*	
	(attributed energy for the extraction of oil/gas used)	*1107*	
	Public administration use		**6814**
	(recorded use)	*6673*	
	(attributed energy for the extraction of oil/gas used)	*141*	
	Commercial use		**10096**
	(recorded use)	*9982*	
	(attributed energy for the extraction of oil/gas used)	*114*	
	Agriculture use		**878**
	(recorded use)	*872*	
	(attributed energy for the extraction of oil/gas used)	*6*	
	Miscellaneous use		**1876**
	(recorded use)	*1821*	
	(attributed energy for the extraction of oil/gas used)	*55*	
"NON-ENERGY USE"	**Non-energy use**		**9763**
	(recorded use)	*9730*	
	(attributed energy for the extraction of oil/gas used)	*33*	
	TOTAL ENERGY USED:		**235148**

Fig. 3.2. Newly defined energy use/user groups for the UK in 2007, using method from Fig. 3.1 and data from '1.1 Aggregate Energy Balance' from [3], also shown in Fig. 3.1. Energy use/user group names are listed in bold with pale blue highlight and the energy uses attributed to them that contribute to them in italic below. Under the column Total Energy Used the left column shows a breakdown of the energy for each use/user group, the single figure on the right of the column for each group shows a group's total. In step 6 these groups will be ranked by the Total Energy Used.

3.2.2.4 Step 4 – Resource extraction (notes)

Extracted resources may be used for energy or non-energy purposes, so energy used in the extraction of energy resources was redistributed to the users that use them, proportional to each user's use of those energy resources. *Losses* incurred by the energy industry were redistributed in Step 3 and this included adding one ktoe to *coal extraction* and 895 ktoe to *oil and gas extraction*.

At this point in the energy pathway circular relationships can be seen. For example: *coal extraction* uses electricity, but *electricity generation* uses coal. 96% of coal use can be attributed to energy industries, with only three ktoe being added to the other 16 use/users of coal. Another complications is that energy used in *oil and gas extraction* is not differentiated between the two in the AEB table [3] (see Fig. 3.1), so as a simple proxy it was assumed that totals for energy use of either would be used to determine redistribution. There was only one user of *primary oils* and this was *petroleum refineries* for transformation into *petroleum products*. For this use/user group only, use of *primary oils* was summed with use of *natural gas* (which was negligible, equating to zero ktoe)[8].

87% of energy use for the extraction of oil was redistributed to the following top energy users of those fuels: 52% to *petroleum refineries* (solely attributed to use of primary oils for transformation purposes), 17% to *electricity generation* (solely attributed to use of natural gas for transformation purposes) and 17% to *domestic* (solely attributed to use of natural gas and according to [3] this can be assumed to be primarily for heating purposes – space heating, cooking and personal hygiene). No other user of *natural gas* represented any more than 2% of use of that resource.

3.2.2.5 Step 5 – Consolidation (notes)

A full list of the new consolidated energy use/user groups is provided in Fig. 3.2 with breakdowns of constituent and attributed energy use. In total 31 use/user groups were determined. Note that there are two groups – *patent fuel manufacture* and *pipelines* – that are missing from the list in Fig. 3.2 because their energy usage was so small as to amount to less than one ktoe. Note also that *pumped storage* has been included under *electricity industry*. This leaves 29 use/user groups.

Lastly, note from Fig. 3.2 that the total of all energy usage is 590 ktoe less than the figure quoted by the AEB table [3] (see Fig. 3.1) for *primary demand* where ideally total energy use and *primary demand* should be equal. This emphasises the lack of accuracy and difficulties arising from attempts to handle national figures for energy usage. What is reported as having

---

[8] *Primary oils* transferred to *petroleum products* were included in the petroleum industry's total use of oil and gas to determine the associated proportion of energy used for the extraction of oil and gas.

been delivered to end-users minus losses from generation, transmission and distribution, is not what is recorded as having been used by those end users under *final consumption* in the AEB table.

3.2.2.6 Step 6 – Rank and display (notes)

The top 88% of energy use for the UK in 2007 is distributed between 11 of the 29 use/user groups and this is ranked by energy use/user groups from most to least energy use in Table 3-1. Of the remaining energy use/user groups not featured in the table, nine groups represented 1% each of the total UK energy use for 2007, whilst the remaining 3% of UK energy use was split across the last nine use/user groups. The breakdown in Table 3-1 is also provided in a pie chart in Fig. 3.3. Note from Table 3-1 and Fig. 3.3 that the top energy use/user groups are the *electricity industry* (23%), *domestic* (19%) and *road transport* (18%). This reaffirms government interest in finding cleaner energy supplies of electricity, heat and transport fuels [27].

Table 3-1: UK energy use/user groups for the top 88% of energy used for year 2007, ranked (largest to smallest).

Energy use/user group	Energy use (ktoe)	% of total
Electricity Industry	54692	23
Domestic use	45123	19
Road transport use	42815	18
Air transport use	13971	6
Commercial use	10096	4
Non-energy use	9763	4
Petroleum refinery	8725	4
Public administration use	6814	3
Other industries	6252	3
Chemicals industry use	5710	2
Food, beverages etc. industry use	3729	2
TOTAL	**207690**	**88**

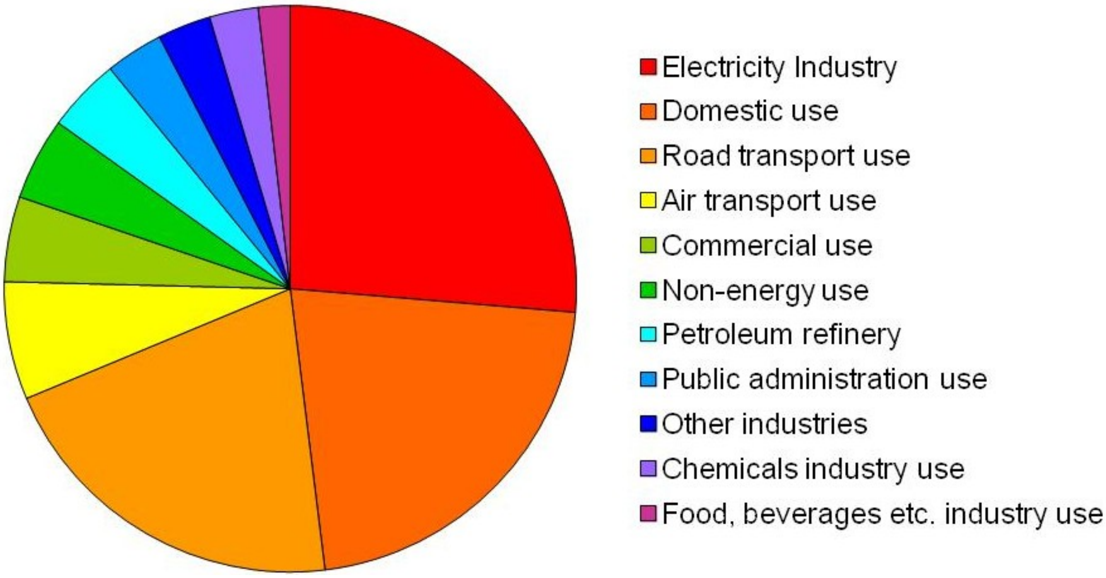

Fig. 3.3. Top energy use/user groups as determined by method described in Fig. 3.1 using data from the '1.1 Aggregate energy balance 2007' table from [3], also shown in Fig. 3.1. Pie chart representative of top 88% of energy usage.

3.2.3 DISCUSSION OF TOP ENERGY USE/USER GROUPS

In this section a closer look at each candidate will investigate their merits as the primary focus for change of energy pathway. Prospects for change are then summarised.

3.2.3.1 Electricity industry

Unlike the *domestic* or *road transport* sectors, theoretically the *electricity industry* is not supposed to be interpreted as being an 'end-user' of energy. In the normal order of things, it is a supplier, concerned with generating and distributing energy to end-users. The fact that such a great amount of energy goes into the *electricity industry* but does not come out at the other end, such that this group comes top of the hierarchy for use, is somewhat disconcerting.

The energy that does not leave the *electricity industry* is primarily in the form of losses, particularly as can be seen in Fig. 3.3, from *transformation* processes for fossil and nuclear-based portions of the input energy mix. As noted earlier, thermal conversion efficiencies of fuel into electricity by UK generators were on average 36.0% for coal, 51.9% for gas and 37.9% for nuclear in the year 2007 [14]. Unlike the case for road vehicles [81, 113] however there are strong pressures to improve the efficiency of new generators, fuel economy of a generator being second only to reliability for an *electricity generation* company. Indeed, the new Staythorpe C gas power station under construction by ALSTOM Power boasts a thermal efficiency of 58% [114].

As newer generators come online and older generators are phased out, efficiency improvements should be made. *Electricity generation* in the UK also already relies on a mix of energy resources as will be shown later and as noted earlier, there are plans to reduce the importance of fossil fuels in that mix [4].

3.2.3.2 Domestic sector

The *domestic* use/user group in Table 3-1 used 45,123 ktoe of energy. The AEB table in [3] reproduced in Fig. 3.1 shows that 9893 ktoe of the energy used was *electricity* supplied by the *electricity industry*. This represents 22% the total energy use by that group. Use of electricity by the *domestic* sector may be for a variety of purposes using a variety of equipment, with a variety of differences in conversion efficiencies at point of use.

Furthermore from the AEB table in [3] it can be noted that 30,090 ktoe of *domestic* energy use was of *natural gas*, energy that it can be assumed was used for a singular purpose: heating - either for cooking, hot water for hygiene or for space heating purposes. Combustion of natural gas is the common method used to get heat and this typically has very high associated efficiencies – conversion of natural gas to useful heat in a modern condensing boiler as noted previously can reach efficiencies upwards of 90% [27].

Domestic energy use in general is directly linked to social factors [115] and personal factors including the perception of comfort [116]. According to Roberts [117], population demographics have a large impact on *domestic* energy use where regulating home temperature is concerned and the high price of purchasing homes has increased demand for rented accommodation where there is little or no incentive to invest in energy saving improvements (e.g. insulation and double glazing).

The predominant means of reducing *domestic* energy use as stated by the government White Paper on Energy [27] – energy efficiency improvements and influencing behaviour – have strong limitations. The prospects for achieving behavioural changes can be related to Maslow's 'hierarchy of needs' in that ascension towards altruism will only occur if more basic needs are satisfied, with the additional problem that perceivably "Man is a wanting animal" [118]. The latter is seemingly reflected by the 'Rebound effect': the additional energy consumption enabled by energy efficiency increases which can result in a net zero-change (or worse, increase) in energy consumption after efficiency has been improved, due to a positive income effect [119]. Meanwhile both household energy use and GHG emissions are strongly related to income levels, with additional factors such as the type of dwelling, tenure, household composition and rural versus urban location also being extremely important [120]. In short, people live to their means.

3.2.3.3 Road transport

In *road transport* fuel is combusted in order to convert chemical energy to kinetic energy. This is consistent across the entire transport sector, with only one other form of energy in use: *electricity* – the total energy for which represented little over 1% of the total for the sector. Use of anything other than *petroleum products* or *electricity* by *road transport* is recorded as insignificant (under 1 ktoe) in the AEB table from [3].

As noted in the previous chapter, there is a conflict of interest for use of *petroleum products*. Non-energy use of fossil fuels – which is integral to the continuation of modern society until alternatives are found and established to match the scale of present demand – is almost exclusively dependent upon *petroleum products*. *Road transport* energy use is thus the main competitor for that resource at least in the UK but likely elsewhere too.

Road transport has several alternative energy pathways open to it, although each has benefits and drawbacks. There is particular concern for emissions from *road transport* because these include emissions that have a direct impact upon human health. The concentration of emissions is primarily proportional to the number of vehicles in a given area, the highest density of which typically coincides with the location of the highest human population densities, compounding the air pollution problem and the subsequent detrimental health impacts that the energy use of fossil fuels by *road transport* has.

Concern for *road transport* in the context of emissions is focused upon the energy use of fuels by combustion mechanisms. Considering 'global' environmental impacts, existing vehicles and potential alternatives using other forms of energy can have vastly differing emissions profiles; they produce differing emission mixes and produce different emissions at differing magnitudes [47, 81, 105, 109, 121, 122]. With regards to local environmental/heath impacts however, reducing vehicle emissions in urban areas may make electricity an appealing option because at point-of-use electricity contributes zero emissions [47, 53].

Air quality has long been of importance in the UK because of its impact and cost to taxpayers through the provision of the National Health Service (NHS). As noted in the previous chapter: it costs the UK £8.5 billion to 20 billion per year in health impacts, potentially cutting life expectancy by many years [48]. In the early 1990s the 'Urban Clear Zone' (UCZ) concept was formed by the Foresight Committee and was originally intended to create more liveable, accessible and lively urban centres [123]. This included imposing access restrictions to these zones within which only 'nil emission vehicles' – public and private transport that produced no air pollution at point of use – would be permitted to travel [124]. At the time however, few viable alternatives to internal combustion vehicles were available, so smaller UCZ were set up in city centres, with restricted access open to pedestrians and public transport only.

Production of vehicles, their maintenance and their end-of-life disposal also have associative emissions [125], although arguably such emissions are not strictly part of the energy pathway for road transport, but part of the energy pathway to industrial end-users. Emissions originating from fuelled vehicles can be and have been mitigated through emissions legislation and regulatory measures such as banning the sale of leaded petrol [5]. Catalytic converters are one of several ways in which vehicle technology has been adapted to reduce emissions [81]. With regards to use of alternative fuels, the emissions profiles of ethanol burning vehicles can also be influenced by gear change speeds for richer fuel mixes [108].

For the existing UK rolling stock, which is as shown by the AEB table in [3] to be virtually exclusively dependent upon *petroleum products*, vehicular emissions are typically higher for older vehicles than newer vehicles and directly relate to vehicle class (e,g. cars, motorbikes, or Heavy Goods Vehicles – HGV) because they are proportional to kerb weight [5]. In his acclaimed Medlock lecture 'CO2 and Cars – *Driving Down the Carbon Footprint'* (2009, 10 Mar), Professor Hawley noted that emissions from road vehicles (concentrating on cars) have been steadily increasing for a number of years. This he stated *"was mainly due to the increasing kerb weight of vehicles"* suggesting the cause of that increase was demand for increased functionality of vehicles, namely in the form of heavy electrical components (e.g. electric windows, CD players, air conditioning etc).

Hawley also noted that there is growing consumer demand for larger and thus more massive vehicles – a finding echoed by [113] in the USA. He also noted that emissions legislation (e.g. mandating that catalytic converters must be added to vehicles) and vehicle safety legislation (e.g. implementation of seat belts) increase the mass of vehicles. Tolouei and Titheridge [126] show that there is usually a trade-off between fuel economy and vehicle safety; this trade-off being related to conflicting influences on a vehicle's mass.

Emissions are also related to fuel economy [81]. Fuel economy in turn contributes to overall energy demand from vehicles, which in light of their almost exclusive dependency upon *petroleum products* is also synonymous with vehicular demand for fossil fuel. As noted by Sovacool [113], however, there has been previously little incentive for vehicle manufacturers to improve fuel economy. Driving behaviour also affects fuel economy and emissions, such that a government initiative called 'Act on CO2' gives advice to drivers on how to cut emissions and save money through reducing the amount of fuel they use by driving sensibly [127].

There is rising concern for the public health impact of ultrafine particulate matter, aldehydes and NO_x, which may lead to future additional legislation for those emissions requiring mitigating components to be added which will increase the kerb weight of all combustion vehicles [81]. This may particularly impact upon kerb weight of vehicles that combust biofuels for sake of aldehyde emissions and perhaps most noticeably upon the kerb weight of H_2

combustion vehicles because they do not require the added mass of catalytic converters until NO_x emissions are considered.

Switching *road transport* to full or partial electricity dependency on the other hand (as in BEV or PHEV) or fuel cells (FCEV), would significantly reduce or eliminate entirely the concern for combustion-related emissions because these technologies are clean at point of use. These alternatives still have other issues in terms of increased vehicle weight affecting energy efficiency. Batteries represent a significant increase in vehicle mass such that hybrids can be up to 10% heavier than a contemporary vehicle of the similar specification [81]. For sake of the actual weight of their principal component (the battery) and the added weight of structural reinforcement required, BEV are at their most economical when battery size is specified to match the distance (range) the vehicle is expected to travel between recharging [128].

It is also worth noting that like the *domestic* sector, *road transport* may face resistance to change. The UK has a vehicle rolling stock legacy: the average lifespan of a car in 2000 was 13.5 years [129, 130]. Sometimes there is social resistance to change in this area. For example there are still a minority of older vehicles which (for practical purposes) are still reliant upon leaded petrol in the UK. Despite being banned for health reasons leaded petrol is still available for purchase by the owners of these vehicles following intense lobbying by the Federation of British Historic Vehicle Clubs (FBHVC); although reduced economic viability of supply may cease the sale of leaded petrol completely in the UK in the future [131]. For another example, increases in road tax through the addition of emissions tax is another government incentive designed to improve the take-up of newer, less polluting vehicles, but this is not being particularly well received by owners of older vehicles [132]. The construction of new generators and building of new transmission and distribution infrastructure can also be a controversial exercise with complex social and psychological factors coming into play [33, 134].

Sovacool [113] highlights a variety of problems that alternative vehicles also face including: research and development, production, marketing and sales, public acceptance and adoption, and long term maintenance. These include resistance in the form of lobbying by powerful pressure groups organised by oil companies, negative perceptions of alternative vehicles by the general public, first-purchase cost, the cost of battery replacements and lack of recharging infrastructure.

In the UK electricity prices are presently more dependent upon supplier costs (which include paying towards infrastructure costs), than the price of transport fuel is dependent upon supplier costs associated with extraction, processing and delivery infrastructure. At least 65% of the price of petrol is contributed to by tax [135] while VAT contributes only 5% to *electricity* bills [136]. Whilst electricity is presently the cheaper option for consumers, this could change if the government, facing a substantial shortfall in tax revenue from users of road transport in the event of a large switch away from conventional *taxed* fuels to alternatives, sought to rectify the matter by applying tax to those alternatives.

3.2.3.4 Prospects for change

Both the *electricity industry* and *domestic* use/user groups are reliant upon a portfolio of energy sources and carriers, whilst *road transport* is almost exclusively dependent upon fossil fuels in the UK, specifically *petroleum products*. Drawing on work from the previous chapter, *road transport* use/user group thus becomes a prime target for three reasons:

- *Road transport* is exclusive dependent upon fossil fuels.
- There is a potential conflict of interest for use of the specific type of fossil fuel (*petroleum products*) that *road transport* is dependent upon because non-energy use of fossil fuels (e.g. in plastics, adhesives, clothing etc.) primarily concerns the use of *petroleum products.* Meaning non-energy use of *petroleum products* is arguably the larger priority for the preservation of civilisation – especially if as expected future availability of or access to *petroleum products* is reduced.
- *Road transport* in the UK is predominantly responsible for the near-term local negative consequences of fossil fuel use (air pollution), because of the methods used by *road transport* to extract energy from fossil fuels (combustion) and because location of use overlaps and is proportional to population density.

Meanwhile there are already plans in motion to further reduce dependency upon fossil fuels for the *electricity industry*, but it is difficult to determine what if any change should apply to the *domestic* energy use/user group, without full energy pathway consideration because electricity is a major constituent of that sector's energy use. The biggest example for conflicting arguments on the matter of *domestic* energy use is heat – assumed to be the biggest purpose for fossil fuel energy use by the *domestic* sector. At point of use *electricity* is the cleaner and more efficient alternative but it is not necessarily the cleaner or more efficient alternative if the *electricity generation* mix involves the combustion of fossil fuels. Biofuels may be the better alternative because as noted previously indigenous supply lends itself to heat and power grade fuels more than transport fuels so use of those fuels should be maximised.

Road transport like *domestic* is a difficult area within which to introduce change, but there are many alternatives, some closer to implementation than others. Many alternatives still involve contribution to air pollution: all forms of combustion and therefore combustion engines using fossil fuels, biofuels or H_2 are less than ideal. This leaves fuel cells and *electricity*. *Electricity* infrastructure is already a feature of nearly every British home, office, school, shop and factory. The addition of transport as a new end-use for electricity would involve extension and possibly reinforcement of an existing network but the provision of H_2 or other fuels for fuel cells may require the construction of an entirely new supply and distribution system.

3.3 CHAPTER 3 SUMMARY

This chapter has drawn together a review of literature on alternative energy pathways, a quantitative analysis of top energy use/user groups in the UK and a review of literature to establish with energy use/user group of the top three has the best prospects for change.

In the quantitative analysis presented here, UK energy use/user groups were ranked by energy using the 2008 edition of the DfT's Digest of UK Energy Statistics (DUKES) report [3] following a regrouping of use/user groups and recalculation of their energy usage, following a method also presented in this chapter. Regrouping was done in order to more fairly attribute energy use listed in the report to energy uses/users relative to the purposes of that energy use, particularly because electricity energy use is otherwise split under several separate headings in the original AEB table in [3]. Three top energy use/user groups were subsequently identified:

- The electricity industry – for which there are already plans to reduce fossil fuel dependency,
- The domestic sector – which represents a massive diversity not only of energy use purposes but types of energy used and barriers to change),
- Road transport – which is known to contribute substantially to detrimental consequences (health-impacting air pollution) arising from energy use of fossil fuels overlapping areas of high population density, and is the primary end use destination of petroleum products – the specific type of fossil fuel for which there is strong conflict of interest for use with regards non-energy use of fossil fuels for the continuation of modern society

It was therefore reasoned that road transport be the primary target for change of energy pathway. Furthermore such a shift would connect the first and third top energy use/user groups (electricity industry and road transport) together, which then might allow “two birds to be struck with one stone”: allowing the top 41% of energy use to be manipulated together as one, perhaps with additional benefits.

The inclusion of electricity within an energy pathway provides that pathway with added flexibility for change at both ends: both where energy is sourced and at point of use. Electricity is clean at point of use which is of special value regards the avoidance of the detrimental consequences of using energy at local scales – this being of particular importance to a nation where the state provides national healthcare services. Chapter 4 will investigate the prospects of this potential relationship between road transport and the electricity industry in more detail.

CHAPTER 4: ENERGY MIX AND ENERGY EFFICIENCY

From the three biggest energy use/user groups identified in the previous chapter (electricity industry, domestic and road transport) it can be said that there are three main energy pathways in use in the UK: *petroleum products*, *natural gas* and *electricity*[9]. Road transport has been highlighted as a key area for change so *petroleum products* and *electricity* have been chosen as the energy pathways of most interest for comparison.

The *petroleum products* pathway was chosen because of road transport's existing and almost complete dependency upon it. The *electricity* pathway was chosen for comparison as the cleanest alternative open to road transport at point of use (a primary concern for road transport), ease its of being introduced as a substitute over H_2 as well as having known plans for reduction of fossil fuel dependency.

In this chapter energy mix and energy efficiency are compared for the two primary energy pathways for the UK to see if there are grounds to switch a key use/user of energy from one to the other. The first part of this chapter focuses on energy mix for the provision of electricity versus fossil fuels. This required the introduction of a method for estimating the fossil fuel dependency of the two pathways.

The second part of this chapter focuses on the added consideration of energy efficiency, comparing the two pathways in the context of providing energy for use in road transport. This involves first a 'well-to-tank' comparison, followed by a 'tank-to-wheel' comparison, followed then by the combination of findings from both in a 'well-to-wheel' comparison to determined if more or less fossil fuel might be used were road transport to switch its energy pathway from *petroleum products* to *electricity*.

'Well-to-wheel' studies try to capture differences in energy delivery pathways between the different vehicles in order to compare possible scenarios for alternative vehicle adoption. These however typically focus upon emissions reduction which is not necessarily the same thing as fossil fuel use reduction. There are many well-to-wheel studies that have investigated the impact upon emissions where grid-derived electricity substitutes fossil fuels in road transport energy use [47, 56, 106, 121, 137] and what each notes is the importance of the two different segments for these types of analysis: well-to-tank and tank-to-wheel.

---

[9] Electricity generation is also the primary endpoint of the pathway for coal use, although less coal is expected to be used for generation in future.

The former in particular is different for every nation and there were few UK-based studies at the time the work in this chapter was conducted. Hammond *et al.* [83] consider the prospect of biofuels for the UK automotive market, but the authors noted (as was noted in the previous chapter's discussion of alternative energy pathways) that there are limitations to the use of biofuels. Offer *et al.* [122] compare BEV to H_2 dependent FCEV and H_2 fuel cell plug-in hybrid vehicles (FCHEV) but omits mention of the fact that H_2 today is primarily sourced from fossil fuels. As with international well-to-wheel studies the focus of the paper was on emissions. It was clear then that for the UK, some rough comparison for the fossil fuel energy input to the two primary energy pathways available for road transport might be useful and so a method for this is presented here.

4.1 ENERGY MIX

Energy flows from extraction through to final use. This sometimes include intermediate steps where energy is transformed from raw materials into some secondary commodity, with trade playing a role in the overall balance of magnitude of resources present at different stages – see Fig. 4.1.

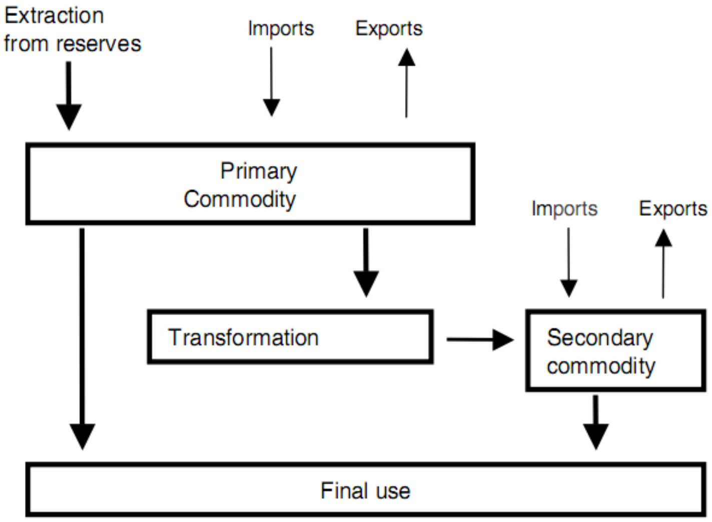

Fig. 4.1. Energy flow from extraction to final use. Figure reproduced from Chart A.1 p.202 of [3], © Crown Copyright 2012.

Reality is unfortunately far more complex. More than one resource can be used for a given purpose and there can be more than one purpose to use any given resource. Worse, secondary commodities may be used in the extraction, transportation and transformation of primary commodities.

> *"In 2007, every 1 toe of secondary electricity consumed by final users required, on average, 1.0 toe of coal, 0.9 toe of natural gas, 0.4 toe of primary electricity (nuclear, natural flow hydro and imports) and 0.2 toe of oil and renewables combined."*
>
> - BERR (in reform), paragraph 1.49 from [3][10]

This quote would seem to give a convenient starting point for looking at the *electricity* pathway but there is no comparative quote regarding *petroleum products* within the same DUKES report [3], meaning that further information must yet be found. Also note that this breakdown does not mention *imports* and the UK was a net importer of electricity in 2007 according to the AEB table from the same report [3]. Although imports are mentioned elsewhere in [3], the fossil fuel/non-fossil fuel mix of imported electricity is not.

The quote (above) also mixes oil with renewable because both contributed a small proportion of the total, meanwhile 'renewables' may in fact include energy from use of waste which may or may not have come from the combustion of breakdown products (e.g. landfill gas) of materials originally manufactured from fossil fuels, such as plastics. Little can be done for the latter but the AEB table [3] used in Chapter 3 to determine energy use/user groups also holds information enabling the separation of oils from renewables. It also notes energy industry use of different fuels for the production of both *petroleum products* and *electricity*.

As such an assessment of energy mix for the two energy pathways of *electricity* and *petroleum products* was derived from calculations and work done here and in Chapter 3 based once more upon figures drawn from the AEB table from [3] unless otherwise specified. The process for this assessment is outlined henceforth.

4.1.1 STEP 1: PRELIMINARY OVERVIEW – ENERGY MIX IN TRANSFORMATION

According to the AEB table in [3] (reproduced previously in Fig. 3.1), for the *electricity* pathway: *transformation* processes had a total input of 82,431 ktoe, incurred *losses* of 49,966 ktoe and had an output of 32,865 ktoe of *electricity*. This is prior to the addition of renewable *primary electricity* transferred to supply without losses and prior to transmission and distribution (and losses incurred there), with no consideration for *imports* and *exports*.

This implies an average input to output efficiency for *transformation* of 39.9% with an energy mix that was 76.8% **fossil fuel** dependent, 22.3% **non-fossil fuel** dependent and 2.0% dependency **unknown** (without knowing the energy mix to point of use of *petroleum products*

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[10] Note: in the quote "secondary electricity" is assumed to be that electricity delivered to end consumers, which is actually a mix of *primary* and *secondary electricity* as noted elsewhere in [3] and mentioned earlier in this Chapter.

and *manufactured fuels*). This assumes, albeit incorrectly, that the *waste* part of the *renewables and waste* fuel used was not in any way derived from fossil fuels.

Renewable *primary electricity* is found in the *transfers* row of the AEB table [3]. If the transfer of 892 ktoe of renewable *primary electricity* to supply is included (note it has no transformation losses because input energy is unknown) then this improves the overall input-output efficiency to 40.5% and the energy mix changes to 76.0% **fossil fuel** dependent, 22.1% **non-fossil fuel** dependent and 1.9% dependency **unknown**. By comparison, the *transformation* stage for the *petroleum products* pathway is 100% dependent upon fossil fuel, specifically *primary oils* which are transformed with little or no losses, so the addition of *primary oils* in the *transfers* row makes no difference to efficiency or energy mix of the *petroleum products* pathway at this stage.

These are not, however, the final energy mixes for the *electricity* pathway or the *petroleum pathway* for road transport and further steps must be taken to combat the following issues:

- Most of the energy that the electricity industry uses is listed under *transformation*, but most of the energy used by the *petroleum industry* is listed under *energy industry use*.
- There is also the energy used in the extraction of raw materials to consider (only coal, oil and gas are listed in the AEB table [3]).
- Some energy inputs are unknown – for example the energy mix of electricity used by other energy industries that use *electricity* and vice-versa.
- Consideration should be given to proposed changes in energy mix of the two pathways (*electricity* and *petroleum products*) that may influence matters (e.g. decarbonisation of electricity generation mix), outlined by the UK Renewable Energy Strategy (UKRES) [4].
- The relative importance of imports with unknown energy mixes should be checked.

Tables were therefore constructed in an Excel spreadsheet to list the inputs made to the production of each *secondary fuel*: *manufactured fuel*, *petroleum products*, *electricity* and *heat*. The **fossil fuel** versus **non-fossil fuel** versus **unknown** dependency was then calculated for each *secondary fuel* based on the breakdown of dependencies for their listed inputs.

4.1.2 STEP 2: INCLUDING ENERGY USED FOR RESOURCE EXTRACTION

The AEB table [3] notes energy used in the extraction of resources, although it does not distinguish extraction of oil (*primary oils*) from extraction of gas (*natural gas*), instead listing them under one heading: *oil and gas extraction*. Energy mixes for *coal extraction* and for *oil and gas extraction* were thus calculated, using figures from the AEB table [3] (see below). *Coal*, *primary oils* and *natural gas* as they are referred to in the AEB table [3] are all forms of fossil fuels themselves so use of them is classed as **fossil fuel** dependency but at this stage the dependency mix for *electricity* is unknown as it has not yet been calculated.

For *coal extraction*:

- 4 ktoe of *coal* (**fossil fuel**)
- 8 ktoe *natural gas* (**fossil fuel**)
- 85 ktoe of *electricity* (**unknown** mix)

$$\frac{(4+8)}{(4+8+85)} \times 100 = \mathbf{12.4\%}$$

Fossil fuel dependency

$$\frac{(85)}{(4+8+85)} \times 100 = \mathbf{87.6\%}$$

Unknown dependency

For *oil and gas extraction*:

- 5523 ktoe of *natural gas* (**fossil fuel**) $= \frac{5523}{(5523+48)} \times 100 = \mathbf{99.1\%}$ **Fossil fuel** dependency
- 48 ktoe of *electricity* (**unknown** mix) $= \frac{48}{(5523+48)} \times 100 = \mathbf{0.9\%}$ **Unknown** dependency

The investigation of energy use/user groups in Chapter 3 divided energy used in the extraction of resources proportionally between the users of those resources (see specifically 3.2.2.4). Using that work, new rows detailing the proportional energy used for extraction of resources attributed to each energy industry, were added to the lists of energy inputs to the production of each *secondary fuel*.

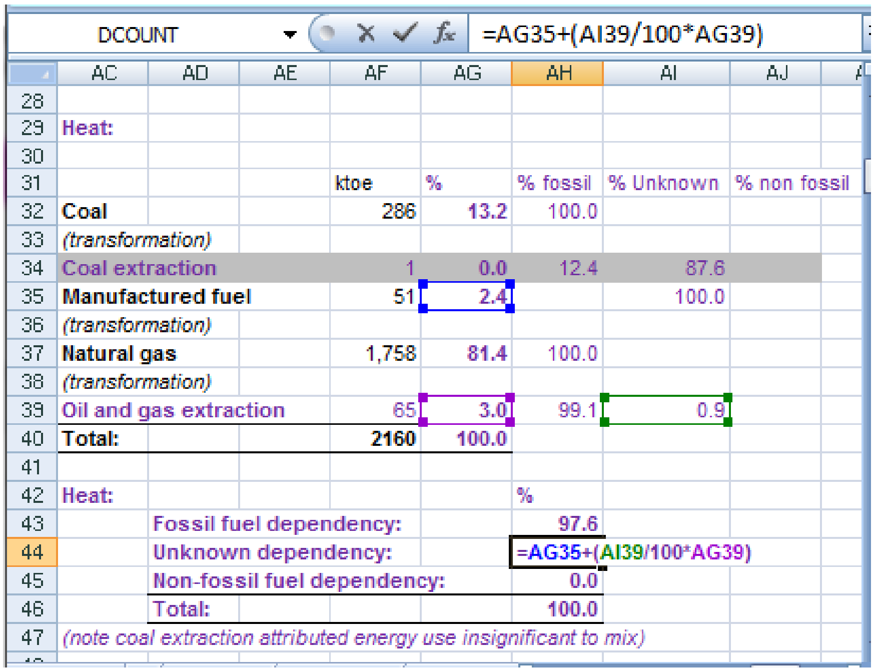
For example: according to the AEB table (miniaturised and reproduced as part of Fig. 3.1 in Chapter 3) in [3], 32,897 ktoe of *coal* was used by the electricity industry for the production of *electricity*. According to calculations made in subsection 3.2.2.4 of Chapter 3, this made the electricity industry responsible for 81.7% of the energy that was used in *coal extraction* and any losses associated with the extraction process, because it was responsible for 81.7% of the total *coal* used by all users. This equated to 80 ktoe of energy.

Having added in energy used to extract coal, gas and oil used in the production of each *secondary fuel* it was then possible to note alongside them the proportional dependency mixes established above. Using *electricity* as the example again, if 80 ktoe of energy was used to extract the *coal* that was then used by the electricity industry to make that *electricity*, then according to the calculations performed at the top of this section, 12.4% of that 80 ktoe was **fossil fuel** dependent, whilst 87.6% of its dependency was **unknown**.

4.1.3 STEP 3: INCLUDING ENERGY INDUSTRY USE

Energy used by energy industries themselves was considered next. The AEB table [3] did not differentiate between use of *coke* and the use of *patent fuel*, mentioning only *manufactured fuel* of which both *coke* and *patent fuel* are subclasses. It was therefore assumed that the sum of energy used by the industries involved in the production of *coke* and *patent fuel* contributed to the energy mix of *manufactured fuel*, portions of which was used by other energy industries for the production of other forms of energy.

This was achieved first by calculating the proportions in which energy inputs contributed to the total energy balance for each *secondary fuel*. Each of the inputs also had a corresponding mix of **fossil fuel** versus **non-fossil fuel** versus **unknown** dependency. By multiplying the percentage contribution of each input to a given *secondary fuel* by the percentage dependency each input had (e.g. **fossil fuel** dependency), these could then be summed to give the overall proportional dependency. Fig. 4.2 shows the example table for the production of *heat*.



=AG35+(AI39/100*AG39)

	AC	AD	AE	AF	AG	AH	AI	AJ
28								
29	Heat:							
30								
31				ktoe	%	% fossil	% Unknown	% non fossil
32	**Coal**			286	13.2	100.0		
33	*(transformation)*							
34	Coal extraction			1	0.0	12.4	87.6	
35	**Manufactured fuel**			51	2.4		100.0	
36	*(transformation)*							
37	**Natural gas**			1,758	81.4	100.0		
38	*(transformation)*							
39	Oil and gas extraction			65	3.0	99.1	0.9	
40	**Total:**			**2160**	100.0			
41								
42	Heat:					%		
43		Fossil fuel dependency:				97.6		
44		Unknown dependency:				=AG35+(AI39/100*AG39)		
45		Non-fossil fuel dependency:				0.0		
46		Total:				100.0		
47	*(note coal extraction attributed energy use insignificant to mix)*							

Fig. 4.2. Screenshot of Excel table made for *heat* showing breakdown of inputs and example cell formula for calculating the percentage of *unknown* dependency.

As before in Chapter 3, **black** font colour indicates figures as they were found in the AEB table from [3], **purple** font colour indicates where the number is the result of a calculation performed in this chapter. In Fig. 4.2 above the inputs for *heat* are listed in the far left column. In the next column, a percentage breakdown is provided indicating the proportion of the total energy input to the production of *heat* that each input constitutes.

The three columns on the right show the distribution of **fossil fuel**, **unknown** and **non-fossil fuel** dependency assumed for each of those inputs. Below the table of inputs the mix of **fossil fuel**, **non-fossil fuel** and **unknown** dependency of *heat* production is calculated. The formula bar in the screenshot indicates the example calculation for establishing the **unknown** dependency whilst the constituent cells are highlighted (clicking on the cell to edit formula highlights the cells involved in the calculation). In number format that equation would be as follows:

Oil and gas extraction was previously calculated as having an energy input for which 0.9% of was of **unknown** dependency.

Oil and gas extraction contributed 3.0% to the total energy input to the production of *heat*.

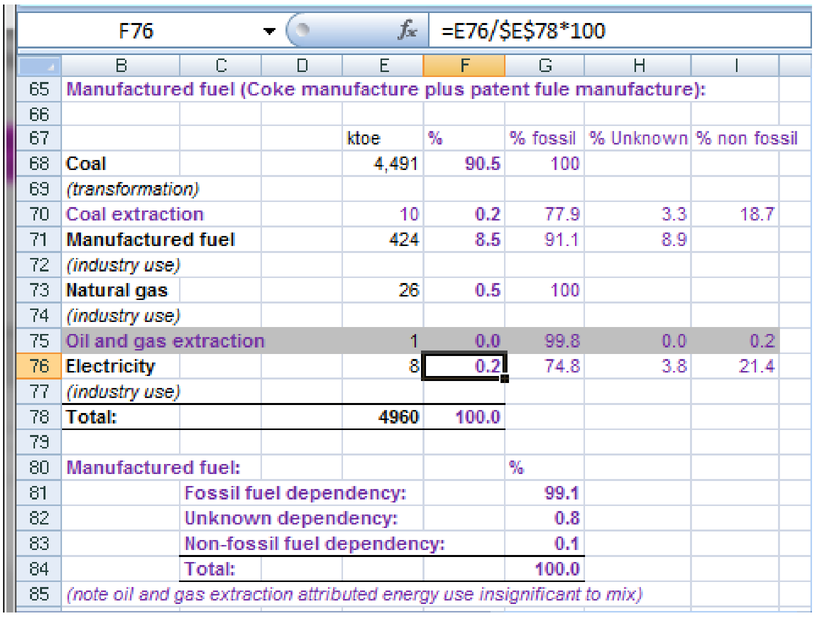
$$2.4+\frac{0.9}{100}\times 3.0 = \mathbf{2.4\%} \qquad = \qquad \textbf{Unknown}\text{ dependency}$$

Manufactured fuel contributed 2.4% to the total energy input to the production of *heat* and all of it (100% at this stage) was deemed **fossil fuel** dependent.

As can be seen in Fig. 4.2, energy used for *coal extraction* constituted less than 0.1% of the inputs to *heat* production. As such in this example energy attributed to *coal extraction* has been greyed out so as not to be included. In this first iteration of the *heat* table, *manufactured fuel* is assumed to have a 100% **unknown** dependency mix. This will change in the next iteration.

4.1.4 Step 4: Account For Interdependency Of Different Fuels

Where the production of a *secondary fuel* included use of other fuels e.g. *electricity*, mixes calculated from the previous iteration were used to fill in the gaps. *Electricity* use for example now has an associated dependency mix (see Fig. 4.3) where previously the mix would have been assumed to be 100% **unknown** dependency.



F76 =E76/$E$78*100

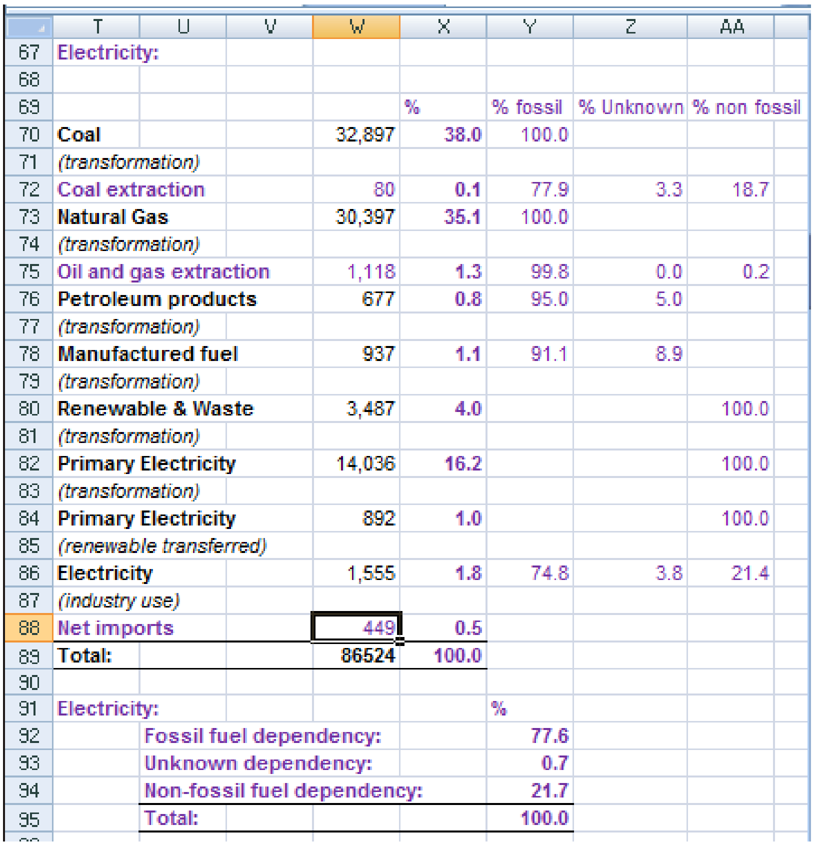
	B	C	D	E	F	G	H	I
65	Manufactured fuel (Coke manufacture plus patent fule manufacture):							
66								
67				ktoe	%	% fossil	% Unknown	% non fossil
68	**Coal**			4,491	90.5	100		
69	*(transformation)*							
70	Coal extraction			10	0.2	77.9	3.3	18.7
71	**Manufactured fuel**			424	8.5	91.1	8.9	
72	*(industry use)*							
73	**Natural gas**			26	0.5	100		
74	*(industry use)*							
75	Oil and gas extraction			1	0.0	99.8	0.0	0.2
76	**Electricity**			8	0.2	74.8	3.8	21.4
77	*(industry use)*							
78	**Total:**			**4960**	**100.0**			
79								
80	Manufactured fuel:					%		
81		Fossil fuel dependency:				99.1		
82		Unknown dependency:				0.8		
83		Non-fossil fuel dependency:				0.1		
84		Total:				100.0		
85	*(note oil and gas extraction attributed energy use insignificant to mix)*							

Fig. 4.3. Second iteration table for *manufactured fuel*. Note use of manufactured fuel to make manufactured fuel, dependency mix for which taken from previous iteration for *manufactured fuel*.

Note that Fig. 4.3 highlights another issue: where there is *own use* of a fuel by an energy industry that makes that fuel. Industrial use of energy for *coke manufacture* and *patent fuel manufacture* (coke and patent fuel being forms of *manufactured fuels*), used 424 ktoe of *manufactured fuels* according to the AEB table in [3]. It was assumed that the energy mix for *manufactured fuels* used could be no less fossil fuel dependent than the previous iteration. Figures for the dependency mix of the production of *manufactured fuels* were therefore taken from the previous iteration of energy mix calculations to provide a conservative estimate for *manufactured fuel* use listed elsewhere. After this second iteration of the process, the **unknown** portion of dependency for any fuel was no higher than 0.8%. This figure was considered satisfactory and no further analysis was undertaken.

4.1.4.1 Resultant mix breakdown for the electricity pathway

The resultant breakdown for the *electricity* pathway is provided in Fig. 4.4. The UK was a net importer of electricity in 2007, importing 449 ktoe of electricity to meet demand. This electricity had an unknown mix for dependency but proportionally would have represented no more than 0.5% of the total energy input so inclusion of net *imports* has had little influence on overall figures for dependency. The overall energy mix as regards to fossil fuel dependency for the electricity pathway was therefore 77.6% **fossil fuel** dependent, 21.7% **non-fossil fuel** dependent and 0.7% **unknown**.



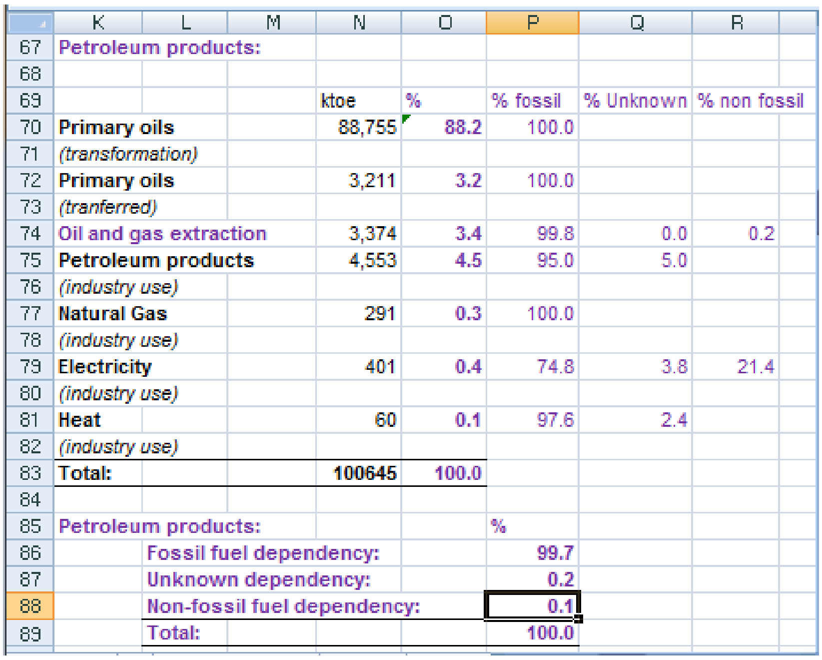
	T	U	V	W	X	Y	Z	AA
67	Electricity:							
68								
69					%	% fossil	% Unknown	% non fossil
70	**Coal**			32,897	38.0	100.0		
71	*(transformation)*							
72	Coal extraction			80	0.1	77.9	3.3	18.7
73	**Natural Gas**			30,397	35.1	100.0		
74	*(transformation)*							
75	Oil and gas extraction			1,118	1.3	99.8	0.0	0.2
76	**Petroleum products**			677	0.8	95.0	5.0	
77	*(transformation)*							
78	**Manufactured fuel**			937	1.1	91.1	8.9	
79	*(transformation)*							
80	**Renewable & Waste**			3,487	4.0			100.0
81	*(transformation)*							
82	**Primary Electricity**			14,036	16.2			100.0
83	*(transformation)*							
84	**Primary Electricity**			892	1.0			100.0
85	*(renewable transferred)*							
86	**Electricity**			1,555	1.8	74.8	3.8	21.4
87	*(industry use)*							
88	Net imports			449	0.5			
89	**Total:**			86524	100.0			
90								
91	Electricity:					%		
92		Fossil fuel dependency:				77.6		
93		Unknown dependency:				0.7		
94		Non-fossil fuel dependency:				21.7		
95		Total:				100.0		

Fig. 4.4. This is the second and final iteration for the calculation of the dependency mix for the *electricity* energy pathway.

4.1.4.2 Resultant mix breakdown for the petroleum products pathway

The resultant breakdown for the *petroleum products* pathway is provided in Fig. 4.5. The overall energy mix as regards to fossil fuel dependency was 99.7% **fossil fuel** dependent, 0.1% **non-fossil fuel** dependent and 0.2% **unknown**. In addition to this it should be noted that according to the AEB table from [3] there was a net deposition of 1429 ktoe of *petroleum products* into storage: 1084 ktoe was removed from *stocks* over the course of the year, but 2513 ktoe was added to *marine bunkers* over that time period. This removed the need to include the removal of fuel from storage in energy mix calculations.

According to the AEB table from [3] The UK is a net importer of *primary oils*, but a net exporter of *petroleum products*. In terms of ktoe, indigenous production of *primary oils* in 2007 – 84,211 ktoe – fell just short by 428 ktoe of the amount of primary used to meet UK demand for *primary oils* – 84,659 ktoe.



	K	L	M	N	O	P	Q	R
67	Petroleum products:							
68								
69				ktoe	%	% fossil	% Unknown	% non fossil
70	**Primary oils**			88,755	88.2	100.0		
71	*(transformation)*							
72	**Primary oils**			3,211	3.2	100.0		
73	*(tranferred)*							
74	Oil and gas extraction			3,374	3.4	99.8	0.0	0.2
75	**Petroleum products**			4,553	4.5	95.0	5.0	
76	*(industry use)*							
77	**Natural Gas**			291	0.3	100.0		
78	*(industry use)*							
79	**Electricity**			401	0.4	74.8	3.8	21.4
80	*(industry use)*							
81	**Heat**			60	0.1	97.6	2.4	
82	*(industry use)*							
83	**Total:**			**100645**	**100.0**			
84								
85	Petroleum products:					%		
86		Fossil fuel dependency:				99.7		
87		Unknown dependency:				0.2		
88		Non-fossil fuel dependency:				0.1		
89		Total:				100.0		

Fig. 4.5. This is the second and final iteration for the calculation the dependency mix for the *petroleum products* energy pathway.

The UK-based petroleum industry, however, imports nearly half as much energy again in the form of *primary oils* and *petroleum products*. The reason behind this according to [3] is that it is more lucrative for the oil companies to export *primary oils* extracted from within the UK to customers across the Atlantic (namely the USA). They then buy the *primary oils* from countries this side of the Atlantic, refining these into *petroleum products* to meet UK demand, again exporting a surplus to customers across the Atlantic.

According to the AEB table from [3] The UK is a net importer of *primary oils*, but a net exporter of *petroleum products*. In terms of ktoe, indigenous production of *primary oils* in 2007 – 84,211 ktoe – fell just short by 428 ktoe of the amount of primary used to meet UK demand for *primary oils* – 84,659 ktoe. The UK-based petroleum industry, however, imports nearly half as much energy again in the form of *primary oils* and *petroleum products*. The reason behind this according to [3] is that it is more lucrative for the oil companies to export *primary oils* extracted from within the UK to customers across the Atlantic (namely the USA). They then buy the *primary oils* from countries this side of the Atlantic, refining these into *petroleum products* to meet UK demand, again exporting a surplus to customers across the Atlantic.

Theoretically this could mean up to a quarter of the *petroleum products* consumed in the UK were transformed from *primary oils* that were not extracted locally using the energy inputs assumed here, meanwhile up to another quarter could conceivably have been sourced from and transformed abroad. Rather than attempt to grapple with this complexity, the simple assumption was made that energy used in the extraction of *primary oils* and during the transformation of them into *petroleum products*, would be applied regardless of where the *primary oils* or *petroleum products* used by the UK originally came from.

4.1.5 STEP 5: CONSIDER FUTURE PROPOSALS FOR CHANGING ENERGY MIXES

Another point to consider is that long term plans exist to increase the proportion of renewable electricity in the UK electricity generation mix and biofuels in the UK's transport fuel mix. The United Kingdom Renewable Energy Strategy (UKRES) report [4] suggested that up to 30% (up from 5.5%) of UK electricity generation could be renewably sourced by the year 2020. Also according to UKRES report [4], renewable fuel must comprise 3.25% of total transport fuel supplied from the years 2009 to 2010, rising to 5% by volume for the years 2013 to 2014, although it is noted that the role of biofuels in the UK is still a contentious issue.

4.1.5.1 Incorporating planned changes for electricity pathway

Starting with *electricity*, it was unknown how such changes would affect the energy mix, or indeed the energy efficiency of the *electricity* energy pathway. In order to get a rough idea, it was decided to assume that the figure for 30% renewables applied to the end-mix for electricity produced through generation (generation assumed here to be the *transformation* and *transfer* sections of the AEB table [3] combined).

First the energy mix minus *renewables and waste* and renewable *primary electricity* (the figure for which was taken from the *transfers* row of the AEB table [3]) was calculated just for *transformation*. It was assumed that renewable *primary electricity* would make up the shortfall for renewables.

Assuming that the existing proportion of *renewables and waste* stayed the same (an input of 3487 ktoe) then at the average efficiency for *transformation* (*electricity generation*) of 39.9% calculated earlier, *renewables and* waste would contribute 1390 ktoe towards the 34,206 ktoe (4.1%) of the electricity assumed required (*generation* output summed with renewable *primary electricity* from the *transfer* row and net *imports*) to meet national demand. It could then be assumed that the remaining 25.9% renewable mix would come from renewable *primary electricity*.

As inputs equal outputs[11] for renewable *primary electricity* transferred in the AEB table [3], this would equate to 8872 ktoe. If the energy input in the form of nuclear *primary electricity* remained unchanged at 14,036 ktoe, then at the average efficiency for transformation of 39.9% calculated earlier, this would contribute 5596 ktoe (16.4%) towards meeting national demand.

---

[11] Input environmental energy is unknown so only output energy is reported in the AEB table from [3].

This leaves 18,348 ktoe (53.6%) which must come from transformation of other fuels and assuming again that this figure would involve *transformation* to electricity at the average efficiency of 39.9%, working backwards that would equate to a required input to *transformation* from other fuels of 46,020 ktoe.

It was assumed the inclusion of *imports* would ignore the fact that with the addition of renewable electricity generation the UK could have a generation surplus, so *imports* were assumed negligible. If the mix for that remaining 46,020 ktoe is assumed to follow that of the same mix of inputs recorded in the AEB table [3], then the breakdown for that input energy would proportionally be as follows:

- *Coal* – 23,324 ktoe
- *Natural gas* – 21,522 ktoe
- *Petroleum products* – 480 ktoe
- *Manufactured fuels* – 664 ktoe

An average efficiency for *transformation* in *electricity generation* has been used throughout these calculations because as noted by The UKRES report produced by the DECC [4]:

> *"Increased levels of renewables deployment could increase the challenges of physically balancing the system. Further work is now needed to identify where and when problems could arise and what needs to be done to address them."*
>
> - DECC, paragraph 7.16 from [4]

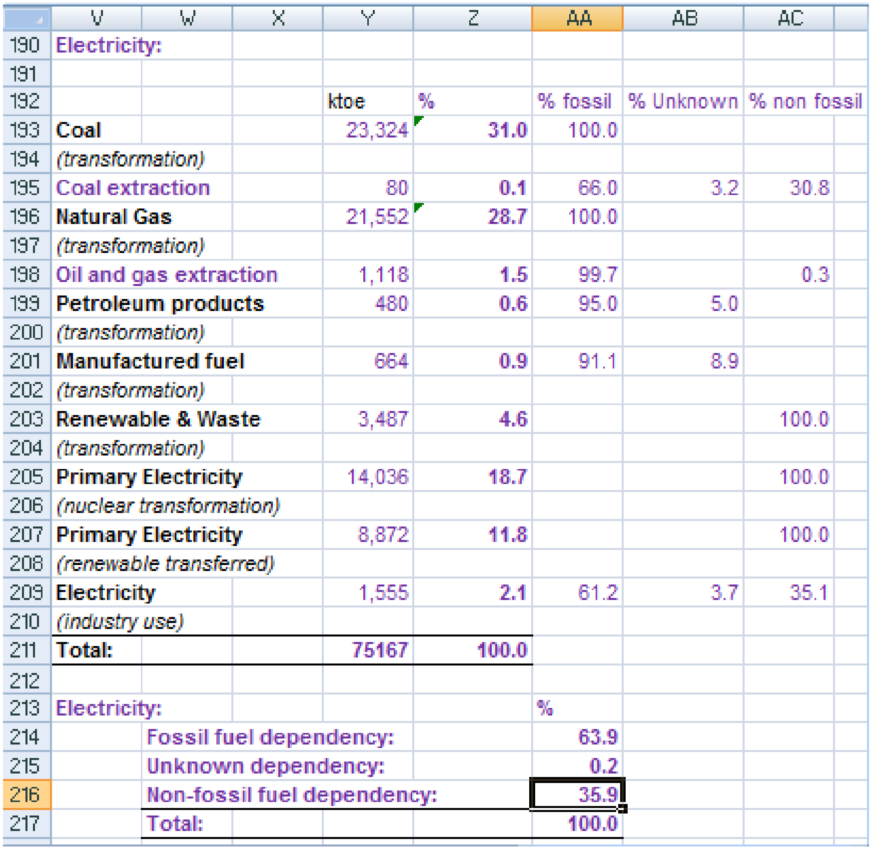
Balancing solutions summarised by the UKRES report [4] included ensuring the supply is sufficiently flexible, which could mean increased ancillary services such as spinning reserves which are typically fossil fuelled [138]; managing demand-side response, which itself has limitations [27]; interconnection, i.e. reliance upon import/export exchanges; and electricity storage. In each case, individually or in combination these solutions could shift the balance of fossil fuel versus non-fossil fuel dependency as well as overall energy efficiency of generation prior to transmission and distribution. The UKRES report [4] proposed that the increase may not cause a severe imbalance at least in the case of wind:

> *"... curtailment [caused by supply exceeding demand e.g. if wind generation were too high when summed with 'must run' generation such as nuclear plants that cannot be quickly turned on and off] is only likely to be a significant issue for levels of wind generation of around 40 GW, which is significantly higher than levels envisaged in this Strategy."*
>
> \- DECC, paragraph 7.17 from [4]

Nevertheless the UKRES report [4] states that more research is needed to fully understand the implications of increasing the proportion of renewable resources in electricity generation. As it can be assumed that there would be unknown contributions from other forms of generation, the use of average *transformation* efficiency for *electricity generation* seemed to best reflect the caution that these estimates be treated as very rough estimates only.

In order to establish the new energy mix at point of use for *electricity* under these assumptions, other figures that in truth may well have changed were assumed unchanged. For example: energy use attributed to the extraction of resources (e.g. *coal*) was previously calculated based upon usage of those resources by the various users and distributed proportionally. Proportional usage and total usage of those resources will however likely change when energy mix changes, although for this analysis will be assumed unchanged. As previously done when calculating energy mix, two iterations were run to account for legacy effects such as own use of products by industry and use of other energy industries' products.

The new breakdown for electricity is shown in Fig. 4.6. The energy mix as for the *electricity* pathway when adding in 30% renewables is: 63.9% **fossil fuel** dependent, 35.9% **non-fossil fuel** dependent and 0.2% **unknown**. Note: There is a knock-on amplification effect for non-fossil fuel content. This arises due to the decarbonisation of other inputs that in turn require electricity in their production.



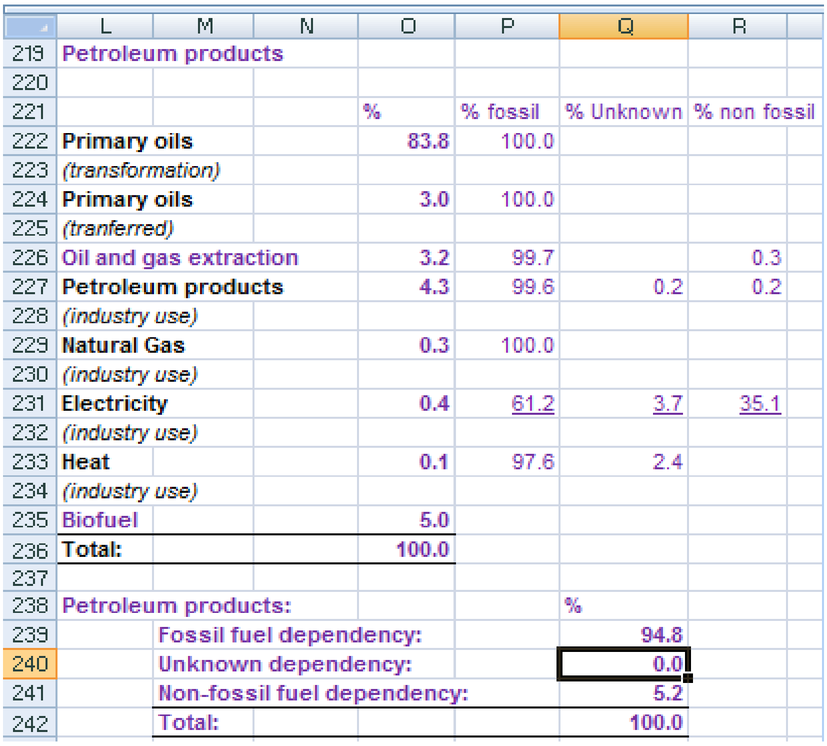
	V	W	X	Y	Z	AA	AB	AC
190	Electricity:							
191								
192				ktoe	%	% fossil	% Unknown	% non fossil
193	**Coal**			23,324	**31.0**	100.0		
194	*(transformation)*							
195	Coal extraction			80	**0.1**	66.0	3.2	30.8
196	**Natural Gas**			21,552	**28.7**	100.0		
197	*(transformation)*							
198	Oil and gas extraction			1,118	**1.5**	99.7		0.3
199	**Petroleum products**			480	**0.6**	95.0	5.0	
200	*(transformation)*							
201	**Manufactured fuel**			664	**0.9**	91.1	8.9	
202	*(transformation)*							
203	**Renewable & Waste**			3,487	**4.6**			100.0
204	*(transformation)*							
205	**Primary Electricity**			14,036	**18.7**			100.0
206	*(nuclear transformation)*							
207	**Primary Electricity**			8,872	**11.8**			100.0
208	*(renewable transferred)*							
209	**Electricity**			1,555	**2.1**	61.2	3.7	35.1
210	*(industry use)*							
211	**Total:**			**75167**	**100.0**			
212								
213	Electricity:					%		
214		Fossil fuel dependency:				**63.9**		
215		Unknown dependency:				**0.2**		
216		Non-fossil fuel dependency:				**35.9**		
217		Total:				**100.0**		

Fig. 4.6. This is the dependency mix for the *electricity* energy pathway when assuming that the output of *electricity generation* (generation assumed to be the *transformation* and *transfer* sections of the AEB table [3] combined) comprised 30% renewable electricity (**non-fossil fuel**).

4.1.5.2 Incorporating planned changes for the petroleum products pathway

For the *petroleum products* pathway, the change in energy mix was only added at point of use and specifically to transport fuels, so assuming that changes to *electricity* and *petroleum products* pathway energy mixes occurred in the same scenario, it can be assumed that all upstream inputs must be adjusted for the added renewable input to electricity calculated previously. It was assumed in order to do this that the proportional mixes input to *petroleum products* applied to 95% of each constituent (in other words divide by 100 then multiply by 95), then 5% for renewable fuels to make up the energy mix to 100% was simply be added at the bottom.

This works so long as it is assumed that *by volume* the proportion of biofuels added to transport fuels would, when combusted, provide the same energy as the rest of the mix. That assumption is not necessarily correct, but at such a small proportional content, it was assumed there would be little in the way of difference in the overall energy released upon combustion of a fuel mix with 5% biofuels compared with none. The full mix is thus as follows in Fig. 4.7.



	L	M	N	O	P	Q	R
219	Petroleum products						
220							
221				%	% fossil	% Unknown	% non fossil
222	**Primary oils**			83.8	100.0		
223	*(transformation)*						
224	**Primary oils**			3.0	100.0		
225	*(tranferred)*						
226	Oil and gas extraction			3.2	99.7		0.3
227	**Petroleum products**			4.3	99.6	0.2	0.2
228	*(industry use)*						
229	**Natural Gas**			0.3	100.0		
230	*(industry use)*						
231	**Electricity**			0.4	61.2	3.7	35.1
232	*(industry use)*						
233	**Heat**			0.1	97.6	2.4	
234	*(industry use)*						
235	Biofuel			5.0			
236	**Total:**			100.0			
237							
238	Petroleum products:					%	
239		Fossil fuel dependency:				94.8	
240		Unknown dependency:				0.0	
241		Non-fossil fuel dependency:				5.2	
242		Total:				100.0	

Fig. 4.7. This is the dependency mix for the *petroleum products* energy pathway, assuming that at point of use, 5% by energy of *petroleum products* used for road transport is biofuel (**non-fossil fuel**).

The energy mix for the *petroleum products* pathway when adding in 30% renewables to the *electricity* pathway and 5% biofuels at point of use for transport fuels is: 94.8% **fossil fuel** dependent and 5.2% **non-fossil fuel** dependent.

4.2 ENERGY EFFICIENCY

There are four sections to this part of Chapter 4. First, energy efficiency of electricity and petroleum products pathways are considered from well to tank. End-use efficiency will be considered next then this will be added onto the well-to-tank analysis to provide a well-to-wheel comparison for both pathways.

4.2.1 WELL-TO-TANK ENERGY PATHWAY COMPARISON

Mixes for the *electricity* and *petroleum products* pathways, both as calculated from the AEB table [3] and with added estimated changes in energy mix, were provided in part 4.1 of this chapter. These can now be coupled with efficiency of delivery to end-users to compare for every one unit of energy in the form of *electricity* or *petroleum products* delivered, how many units of energy in the form of fossil fuels must go into each pathway.

Fig. 4.4 showed 86,542 ktoe of energy went into the *electricity* pathway. Summing the *transformation* output with (renewable) *primary electricity* 'transferred' and net *imports*, then minus the electricity *losses* in transmission and distribution, this amounts to 31,936 ktoe of *electricity* delivered to final consumers of electricity[12]. The pathway efficiency to point of use is thus 36.9% for *electricity*. When coupled to calculations for dependency mix this would mean that for every 1 ktoe of energy in the form of *electricity* delivered to end-users, 2.7 ktoe of energy went in, of which 2.1 ktoe (77.6%) was **fossil fuel**.

The total input to the *electricity* pathway is assumed to change with changing input energy mix. When renewables content is augmented by increasing the proportion of renewable *primary electricity* such that this plus the original contribution of *renewables and waste* constitutes 30% of *electricity* output from the *transformation* stage of the pathway, transformation losses are assumed to be reduced leading to a reduced requirement for total energy input. In Fig. 4.6 this amounted to an input of 75,167 ktoe of energy.

If it is assumed that the rebound effect [119] as cited earlier in Chapter 2 holds sway over industrial energy use, then any reduced demand in energy products associated with electricity generation or provision of materials for electricity generation will be compensated for by a rise in demand from other users. Energy industry users' demand for *electricity* is thus assumed to remain unchanged. Output is assumed unchanged at 31,936 ktoe of *electricity* delivered to end-users after transmission and distribution *losses* which are also assumed unchanged. The pathway efficiency to point of use is therefore improved, now 42.5% for electricity. When coupled to calculations for dependency mix this would mean that for every 1 ktoe of energy in the form of Electricity delivered to end-users, 2.4 ktoe of energy went in, of which 1.5 ktoe (63.9%) was **fossil fuel**.

Making the same comparisons for the *petroleum products* pathway is simpler because it was assumed that total input energy change would be negligible. This, however, may not be true but there was insufficient data available to investigate the sources and energy input to biofuel production for the small amounts used in the UK. Fig. 4.5 shows the total input energy to be 10,0645 ktoe.

When transformed *petroleum products* are summed with those in the *transfers* row (moved from *primary oils* to *petroleum product* columns), the amount of energy delivered to end-users was 91,989 ktoe, with negligible *losses* from distribution. The pathway efficiency to point of use is thus 91.4% for *petroleum products*. When coupled to calculations for dependency mix this would mean that for every 1 ktoe of energy in the form of *petroleum products* delivered to end-users, 1.1 ktoe of energy went in, of which 1.1 ktoe (99.7%) was **fossil fuel**.

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[12] When this calculation is based on recorded use, there is a difference in the calculation of 130 ktoe.

When it was assumed that at point of use 5% of fuel delivered to road transport was biofuel (where *by volume* was assumed to equate to *by unit energy*) and those biofuels assumed were assumed to be 100% renewably sourced, this changed the dependency mix to 94.8% **fossil fuel** as shown in Fig. 4.7. So for every 1 ktoe of energy delivered to end-users in the form of *petroleum products*, 1.1 ktoe of energy went in, of which 1.0 ktoe (94.8%) was **fossil fuel**.

4.2.2 TANK-TO-WHEEL – CONSIDERING END-USE EFFICIENCY

> *"To state that an electric motor is more efficient than a diesel engine, ignores the larger upstream losses from electricity generation and distribution that are linked with the electric motor."*
>
> - Cullen and Allwood, from page 2065 in [6]

Certainly these comparisons support the above quotation, as to point of use (but not including use), even when the provision of electricity is 42.5% efficient and reduced to 63.9% **fossil fuel** dependency, the calculations show that more energy, and more to the point more fossil fuel, would have to go into providing the same amount of energy as *electricity* as opposed to *petroleum products*. More than twice as much energy must be input to provide electricity and worse still, more fossil fuel is ultimately used. What has not been considered yet is the reverse of the quote above: that to state that there are larger upstream losses and energy costs for electricity generation than petroleum products is to ignore the relative efficiencies at end-use.

Plug-in vehicles – vehicles that rely in whole or part upon electricity from the grid for their energy needs – provide a potential avenue for shifting road transport energy use from dependency upon the *petroleum pathway* to the *electricity* pathway. Of greater relevance here is that plug-in vehicles are also well known for doing comparable work but for a fraction of the energy input. Paul Brandon of Kingston University in a presentation to the Bath Royal Literary and Scientific Institution (BRLSI) described how the comparative energy efficiency of an electric motorbike is far higher than that of a fuel powered motorbike when energy available from onboard storage is translated into useable energy – see Table 4-1.

Vehicles that employ electronics for motive power boast high efficiencies although there seems to be some dispute over exactly what those efficiencies are. Jorgensen [105] suggests 80-85% while Cullen and Allwood [6] quote a more conservative estimate of 60%. Would a shift in dependency by changing the energy pathway for road transport from *petroleum products* to *electricity* bring about an increase or a decrease in overall fossil fuel use? An estimated answer to this question will be provided in the next section, combining the well-to-tank and tank-to-wheel assessments made here into a well-to-wheel comparison or the two pathways.

Table 4-1: Comparison of storage methods and efficiency of energy delivery between a battery electric and similarly-ranged petrol-driven motorbike[1].

Storage type:	100 kg Li-ion Battery	3.5 l Petrol tank
Energy Density (specific energy):	120 Wh/kg (0.43 MJ/kg)	32 MJ/l (42 MJ/kg)
Energy available:	43 MJ	113 MJ
Energy efficiency:	90 %	35 %
Useable energy:	39 MJ	40 MJ
[1] Figures are as described by Paul Brandon, Kingston University in a presentation to the BRLSI on "Isle of Man Zero Emissions Grand Prix: one team's entry" on 2nd Dec 2009.		

4.2.3 WELL-TO-WHEEL – PATHWAY COMPARISON FOR FOSSIL FUEL USE

The amount of energy used by road transport vehicles in 2007 was provided in the 2008 edition of the Transport Statistics Great Britain (TSGB) report by the Department for Transport (DfT) [5] in units of million tonnes of DERV and Motor spirit and shown in Table 4-2. These volumetric figures must first be converted into units of energy – specifically Joules – using the following conversion factors provided in [5] and consistent with those stated in the DUKES 2008 report by the DECC [3]: 47.1 GJ per tonne for motor spirit (commonly referred to as 'petrol') and 45.5 GJ per tonne of Gas/diesel oil (DERV, also known as 'diesel'). Previous calculations were made in ktoe (thousand tonnes of oil equivalent) – a unit used by the DECC [3] on the basis that one toe has an energy content of 41.868 GJ. For consistency, figures for fuel use must be converted again into ktoe. The conversion of volumetric figures for road transport into GJ and then ktoe are also shown in Table 4-2.

Table 4-2: Fuel use by different road transport classes in 2007, taken from [5] and converted into GJ and subsequently ktoe using conversion factors from [3].

Type of fuel used	Road transport class	Fuel used, in millions of tonnes (Gt)	Fuel used, in gigajoules (GJ)	Fuel used, thousands of tonnes of oil equivalent (ktoe)
Motor spirit	Cars & Taxis	16.76	789396000	18854
	Light goods	0.42	19782000	472
	Motorcycles	0.14	6594000	157
DERV	Cars & Taxis	4.78	217490000	5195
	Light goods	6.11	278005000	6640
	Heavy goods	8.53	388115000	9270
	Buses & Coaches	1.62	73710000	1761
Totals:	**All transport**	**N/A**	**1773092000**	**42350**
Note: propane use by road transport was considered insignificant (only 0.12 million tonnes) and was subsequently omitted from these calculations.				

The “useful energy” that was extracted from these amounts of fuel used was estimated (see Table 4-3). In order to do this, it was assumed that whole-vehicle efficiencies for fuelled vehicles were synonymous with the fuel-to-kinetic energy conversion efficiencies stated in [6], which were: 13% for ‘petrol’ (Motor Spirit) and 22% for ‘diesel’ (DERV) engines.

Table 4-3: Assumed useful energy extracted by fuelled vehicles in 2007 based on fuel use data from [5][1] and conversion efficiencies from [6][2].

Road transport class	Fuel type	Fuel used (GJ)	Fuel used (ktoe)	Estimated useful energy extracted (GJ)	Estimated useful energy extracted (ktoe)
Cars & Taxis	**Motor spirit** (petrol)	789396000	18854	102621480	2451
Light goods		19782000	472	2571660	61
Motorcycles		6594000	157	857220	20
Cars & Taxis	**DERV** (diesel)	217490000	5195	47847800	1143
Light goods		278005000	6640	61161100	1461
Heavy goods		388115000	9270	85385300	2039
Buses & Coaches		73710000	1761	16216200	387
All transport, all fuels:		**1773092000**	**42350**	**316660760**	**7563**

[1] Original units of ‘million tonnes of fuel’ (Gt) converted into ‘thousands of tonnes of oil equivalent’ (ktoe) using conversion factors from [3].

[2] Conversion efficiencies used from [6] were 13% for petrol engines, 22% for diesel.

From these figures for useful energy, the amount of energy in the form of electricity that would have been delivered to electric vehicles can be estimated. It was assumed that for electric vehicles the conversion efficiency of electricity-to-kinetic energy of 60% stated in [6] was equal to the whole-vehicle efficiency. The amount of useful energy estimated to have been extracted for use by road transport in Table 4-3 was therefore shown to be equivalent to 60% of the total energy delivered to vehicles had electricity been the energy pathway used. From this the assumed required input energy if electricity were to be the energy pathway of choice is shown in Table 4-4.

Energy that must be delivered to end users is dependent upon two factors: the energy required by the end-user to do work and the efficiency at which that end-user is able to convert energy provided into useful energy. As such, a potential reduction in energy that must be delivered to road transport can therefore be seen when comparing the two energy pathways. 12,606 ktoe must be delivered to road transport if *electricity* is assumed the energy pathway of choice, compared with 42,350 ktoe of energy when *petroleum products* were used.

Table 4-4: Energy delivered to road transport had electricity been the energy pathway of choice, estimated using the assumed useful energy extracted by fuelled vehicles in 2007 and assumed whole-vehicle efficiency of 60%[1] in Table 4-3.

Road transport class	Useful energy (GJ)	Useful energy (ktoe)	Estimated input energy (GJ)	Estimated input energy (ktoe)
Cars & Taxis[2]	150469280	3594	250782133	5990
Light goods[2]	63732760	1522	106221267	2537
Motorcycles	857220	20	1428700	34
Heavy goods	85385300	2039	142308833	3399
Buses & Coaches	16216200	387	27027000	646
All transport, all fuels:	**316660760**	**7563**	**527767933**	**12606**

[1] Conversion efficiencies from [6] for electricity-to-kinetic by electric motors assumed to be whole-vehicle efficiency.

[2] In tables 4-3 and 4-4, the energy use within the groups 'Cars and Taxis' and 'Light goods' were divided by fuels used (DERV and motor spirit have different calorific values), but in this table all vehicles are assumed to be dependent upon electricity so their energy use can been summed and consolidated.

As established by section 4.1 of this chapter, if the same amount of energy were delivered in the two forms of *electricity* and *petroleum products*, then up to twice as much fossil fuel would be required to provide that energy in the form of *electricity* versus *petroleum products*. Here, however, it can be seen that the relative efficiency of end-use of the two energy pathways means that the energy that must be delivered to electric vehicles in the form of *electricity* is just under a quarter of that which would be required to be delivered in the form of *petroleum products* in order for contemporary internal combustion vehicles to extract the same amount of useful energy to do work.

4.2.4 SUMMARY: ENERGY PATHWAYS COMPARISON FOR ROAD TRANSPORT

So how does switching to electricity affect the overall amount of fossil fuel input to energy pathways for road transport? Would more or less fossil fuel be used if road transport were to switch from *petroleum* products to *electricity* dependency?

The analysis suggests that the overall fossil fuel input would decrease. Using efficiencies and mixes established in section 4.2.1 of this chapter, the delivery to road transport of the 42,350 ktoe in the form of *petroleum products*, would have required an input of fossil fuel to the *petroleum products* pathway of 46,179 ktoe. Meanwhile the delivery to road transport of 12,606 ktoe in the form of *electricity* would have required an input of fossil fuel to the *electricity* pathway of 26,948 ktoe – almost halving the amount of fossil fuel used.

If, as also calculated in 4.2.1, some changes to energy mix are incorporated; specifically 30% renewables for electricity generation and 5% renewable biofuels for road transport fuels, then the difference is more substantial. An input of 43,936 ktoe of fossil fuel would be required if road transport was reliant upon *petroleum products*, whereas 18,968 ktoe of fossil fuel required if road transport was reliant upon *electricity*.

All in all, a shift to *electricity* from *petroleum products* for road transport would result in a net reduction in fossil fuel use by 42.6% without any government proposed changes in energy mixes for *electricity* or *petroleum product* pathways, 58.9% if electricity mix was improved whilst transport fuels remained unchanged, 56.8% if both electricity generation and transport fuel mixes were improved and 39.7% if transport fuel mix improved but electricity generation mix remained unchanged.

4.3 ROAD TRANSPORT – PROSPECTS FOR CHANGE

Developments in UK road transport are reviewed in this part of Chapter 4, followed by a summary of innovative ideas found from literature for how road transport and the electricity system might interact in future. Lastly drawbacks in literature reviewed are highlighted, indicating reasons to further research the near-term implementation of recharging demand management that avoids the requirement for complex monitoring, communications and third party control mechanism whilst preventing the exacerbation of existing demand peaks.

4.3.1 DEVELOPMENTS IN UK ROAD TRANSPORT

An analysis that used summary statistics for the National Travel Survey (NTS) by [139] suggested that daily average distance travelled by all vehicles is under 20 miles, so alternative vehicles such as BEV with lesser mileage ranges compared to existing vehicles could still be feasible. At least for the UK, plug-in vehicles – BEV and PHEV – appear to be the focus of the greatest push towards changing energy pathways for road transport.

Less than 0.1% of UK's 26 million cars were electric when the UK government released plans to support a ‘green motoring transformation’ [140]. Support for the future adoption of alternative vehicles including PHEV and their necessary charging infrastructures amounted to £250 million to be provided by the government, including a £2000-£5000 cash incentive to buy BEV or PHEV when they become commercially available (this was expected to be for 2012) and £20 million for charging points and infrastructure focusing on cities [141]. Despite government cuts, subsidy grants of £5000 for first time buyers of plug-in cars were set to be introduced in January 2012 following a press release [142].

A number of plug-in vehicle trials were taking place in the UK. The CABLED (Coventry and Birmingham Low Emission Demonstrators) ‘Ultra-Low carbon vehicle trials’ were running in the Birmingham and Coventry area, with three manufacturers contributing the following zero-emission vehicles – all of which are BEV – for the 18 month trial: 25 Mitsubishi iMiEVs, 25

Tata Indica Vista EV and 40 SmartFortwo electric drive vehicles [143-145]. The CABLED consortium includes Mitsubishi/Colt, Mercedes Benz/Smart, Tata Motors, E.ON, Jaguar/Land Rover, LTI, Microcab Industries, Coventry University, Aston University, University of Birmingham and Arup [146]. Meanwhile the Renault-Nissan Alliance signed an agreement with Milton Keynes Council who through government funding were planning to implement 430 vehicle recharging points, to encourage public adoption of their zero-emission vehicles [147].

Honest John (honestjohn.co.uk) [148] reported plans also for FCHEV trials to be run in London as Toyota and EDF Energy worked together to enable the London leasing trial as part of the Technology Strategy Board's Ultra Low Carbon Vehicle Demonstrator Programme. Details reported were:

- Toyota is running a global initiative that will see 600 plug-in Prius trialled, 200 of which will be in Europe.
- EDF Energy working with the Greater London Authority will place 550 public recharging points across London.
- Data will be collected via charging points about recharge demand and timing. The trial will benefit from funding support from the UK Government through the Office for Low Emission Vehicles (OLEV).

Alternatives to plug-in vehicles are also still being supported as well, representing other energy pathway changes. For example [149] reported that Lotus would be showcasing a small number of FCVs – specifically Black Cabs – in London for the 2012 Olympic Games.

4.3.2 INNOVATIVE IDEAS FOR FUTURE PLUG-IN VEHICLES

Israeli-backed company 'Better Place' who are based in California, have come up with a battery leasing programme, whereby cost of first purchase of plug-in vehicles can be brought down by not paying for the battery when they buy the car but instead by renting it separately [150]. This coupled with a focus on getting necessary infrastructure into place has enabled Better Place to partner with the Renault-Nissan Alliance, electricity companies and with governments around the world including Israel, Australia, Denmark and parts of the USA as a provider of intelligent infrastructure and to act as an integrator [150].

Perhaps the most interesting development has been the rise of concepts relating to the use of plug-in vehicles for grid balancing purposes when they are not required by their owners for travel (see Table 4-5). Note that "V2G" refers to vehicle-to-grid power.

Table 4-5: Benefits arising from the development of the relationship between plug-in vehicles and the electricity supply system. Table reproduced from project work presented at the 2nd IEEE PES Innovative Smart Grid Technologies conference in 2011 [151].

Potential Benefits	How achieved
Load limitation for network infrastructure and conservation of electricity generation capacity.	Scheduling recharging of plug-in vehicles to avoid existing demand peaks.
Increased electricity generation efficiency for fuel-based generators.	Providing fuel-based generators with greater operational stability by targeting recharging of plug-in vehicles to coincide with predicted lulls in demand so as to level overall demand.
Increased renewable electricity dependence.	A) Making plug-in vehicle recharging load adjustable according to the availability of supply of renewable electricity. B) Use of vehicle batteries as flexible energy storage (V2G).
Reduced necessity for fuel-dependent fast-dispatch flexible generators that handle ancillary services such as the provision of spinning reserves.	Allowing plug-in vehicle batteries to perform some of these functions through V2G.

The simplest concept is that of valley-filling in order to level demand, increasing the relative proportion of the base-load. ‘Base-load’ is the proportion of demand that does not diminish: the minimum below which demand never falls. Base-load offers two opportunities:

- It is perfectly suited for any type of generation that is classed as ‘must-run’ i.e. types of generation whose costs cannot be reduced during periods of disconnection e.g. by being switched off or whose output is not easily ramped up or ramped down.
- Stable demand means stable output required from supply, which for a fuel-based generator means constant output and therefore constant operating state allowing this to be set at the greatest operational efficiency.

Nuclear generation is one example of must-run generation: disconnection does not signify a reduction in running costs or energy output (they cannot be conveniently ‘switched on and off’ like fuelled generators), so to get the best out of the investment and avoid wasted energy, nuclear generators are usually assigned to the provision of base-load supply. Arguably many forms of renewable generation are also must-run. The sun cannot be switched off, nor can the wind. Whenever intermittent energy resources for renewable electricity generation are available to be used they should be utilised, so as to minimise requirements for energy storage.

All machines have an optimum efficiency and ramping output up and down usually increases wear and tear and compounds losses, but ramping output up and down is often necessary to regulate electricity grids [152]. In the UK, older fuel-based (combustion) generators cover the remaining base-load, ramping output up and down in accordance with seasonal variations. Further fuel-based (combustion) generators then provide supply for the greater diurnal oscillations in demand. The majority of fuel-based (combustion) generators in the UK rely upon fossil fuels.

If electricity demand could be levelled so that less of such regulation was required, then generators could potentially operate at optimum efficiencies for longer periods. A less variable and more predictable demand profile would also reduce the need for spinning reserves – ancillary services in the form of generators that connect and disconnect (usually called 'spinning reserves' because they remain turned on and burning fuel even when they are not contributing to the grid) as required to meet peaking periods.

Kintner-Meyer *et al.* [153] initially used seasonal averages when investigating the impact of PHEV in regional U.S. power grids. Whilst there might be a few days out of the year in which they assumed PHEV might not be fully recharged (presumably enforced by pricing or load control methods), any shortfall in a vehicles energy requirements could be made up by onboard fuel storage coupled with an internal combustion engine.

This form of valley-filling could help level demand across seasons, but more often targeted are the diurnal fluctuations in national demand. The (UK-based) King Review of Low Carbon Cars [154] notes that uptake of plug-in vehicles may be promoted by the fact that electricity is cheaper than petrol or diesel "... especially if cars are charged overnight when electricity demand is lower and there is spare capacity" (paragraph 3.35, p33, ch3 Fuels for the Future).

Many researchers have gone further than this, inspired by the potential of vehicles as providers of ancillary services (most notably vehicle-to-grid or 'V2G') and to enable demand flexibility towards the intermittency associated with higher renewable energy mixes for electricity generation [138, 150, 152, 155-157]. Furthermore, some automotive manufacturers are already claiming that their vehicle batteries will be unharmed by part-recharging [158].

Unfortunately at the start of the study, there was very little reported UK-based research into V2G and in fact there was very little in the way of papers relating to UK adoption of plug-in vehicles, although some studies looking at distribution network level interactions were underway [159, 160]. A problem arises here because the more complex the interaction between vehicle and grid, the more complex the system for implementing that relationship needs to be. Complex systems and customer relationships along with the necessary legal regulations to protect consumers and those who design, implement and maintain mechanisms for two-way communications and monitoring, rarely develop overnight. They usually evolve over time as and when need requires and/or viable opportunity arises.

There have been concerns for the unmitigated impact of plug-in vehicle associated new demands for electricity, especially if the demand control mechanisms (assumed to be mature and available in most smart-recharging and V2G studies) are not in place if, when plug-in vehicles targeted at mainstream buyers were released for sale, customer demand were to grow faster than the technology needed to accommodate plug-in vehicles in this way.

In the US, Yang [104] noted that in the case of H_2-based FCEV there would be coincidence between existing electricity demand peaks times where electricity would be used to generate H_2 fuel, both over a daily and seasonal time frame. Arguably this is likely the case also where electricity is the ‘fuel of choice’ for road vehicles. Electricity usage is always highest when people are not travelling, corresponding also to when a plug-in vehicle is likely to be parked, not in use and the user will find it convenient to recharge that vehicle’s battery.

In Japan, Koyanagi and Uriu [140] modelled the importance and benefits of introducing a regional time shift in the recharging of electric vehicles to ensure that demands are levelled across areas of a distribution network according to existing patterns in local demand. A UK study suggested that “At the national level, full penetration of Electric Vehicles (EVs) and Heat Pumps (HPs) could increase the present daily electricity consumption by about 50%, while doubling the system peak” (paragraph 1.4 [140]). Timing of demand is evidently a key issue and there has been little research into ways to structure the timing of plug-in vehicle specific electricity demand <u>prior</u> to the implementation of complex communication systems for monitoring and third party control of plug-in vehicle recharging.

4.3.3 DRAWBACKS AND SHORTFALLS OF LITERATURE REVIEWED

Nearly all literature so far reviewed has unfortunately focused upon long-term prospects for plug-in vehicles, ignoring the fact that many mainstream plug-in vehicles were due to be released for sale in the UK in the following 12 months. Much research worldwide has gone into the vision and design of ways in which use responsive plug-in vehicle recharging demands to adjust the impact of plug-in vehicle recharging on electricity supply networks (or provide grid services at the same time) [56, 138, 139, 150, 152, 157, 160-176].

Of all these research papers, however, all assume that if recharging is controlled at all, it is controlled by a third party via smart metering or charging boxes. Where it is assumed that vehicle owners are controlling recharging, only one ‘off-peak’ time slot for recharging is considered. Otherwise it is assumed vehicles recharge upon arrival home or at the end of a journey. Several do not mention the means for which recharging might be controlled, if that is assumed as part of their work, at all.

There are several problems with this pattern of present research focus. The first is that it has been assumed that a complex monitoring and control schemes would be instantly welcomed and adopted by consumers the moment they were put in place, at a time when there has been much negative press regarding the monitoring of people's daily lives and activities by third parties via cars [177], Smart Meters [178] and Facebook [179]. It also assumes that such schemes and their physical mechanisms would be manufactured and in place, either from day one where there was minimal demand for vehicles and their future numbers uncertain (a questionable investment if once again, the plug-in vehicle proved itself inappropriate for the mass market), or just before vehicle recharging hit a threshold that would start to cause the electricity supply network problems.

Assuming no stepping stone between then and now, especially where this concerns the promotion of adoption and acceptance of such a third party recharging and control mechanism from a human behavioural perspective, is a very large gamble. It is an especially large gamble when there is no previous technology or scheme in place for early-adopters of plug-in vehicles to get used to, or to build trust towards accepting the authority and competence of a third party to monitor and control their vehicle's recharging activity. The social ramifications of waiting until sufficient plug-in vehicles are in use as to justify building a third party recharging monitoring and control system, are unknown.

It could potentially be years into vehicle ownership for the first owners, during which time behavioural patterns and habits will be formed around recharging practises that set trends by example for new owners too. Waiting until then before placing restrictions on recharging such that control of recharging be removed from owner and given to a third party, may result in consumer resistance instead of interest in, support or demand for such a system.

None of the literature reviewed considered the intermediate timeframe between early adopters of new vehicle technology and nationwide implementation of functional vehicle recharge monitoring and control systems. None so far have addressed the issue of social acceptance of third party monitoring and control of recharge scheduling, or mentioned that this is even an issue that warrants investigation.

Estimations of plug-in vehicle population sizes based on their suitability for ownership by UK households (a consumer demand perspective) are also lacking. This may be the case because to undertake such an investigation would require a great deal of time pulling apart social data that is not collated in a way that is easily fit for such a purpose. The main resource that is available for the UK is the NTS (National Travel Survey) [1] which is primarily a social and economic database used to investigate things like how income affects the likelihood of a person to travel by walking, public transport, or by different classes of personal vehicles. A recent review of European mobility surveys by Pasaoglu et al. [180][13] for their potential to support studies on the impact of electric vehicles on energy and infrastructure needs in Europe, confirms this assertion.

Prior to 2013, the only reference made to the UK's NTS by researchers in the field of plug-in vehicle load modelling that could be found was a report by Centre for Sustainable Electricity and Distributed Generation, Imperial College [139], and a paper by Bonilla [181], both of which used only the statistical summaries available on the DfT website. It seems that papers reporting upon the research for this thesis, [151, 182] were the first to draw attention to potential usefulness in directly consulting the NTS as a database, rather than just relying upon the statistical summaries of that database.

Awareness and understanding of the NTS as a database available for analysis has been so poor that incorrect assumptions have even been made about the information it contains. Bonilla [181] stated that the NTS doesn't report data on diesel mileages because it monitors vehicle counts without recording vehicles by engine type. Direct consultation of the NTS database and the criteria it covers would have shown, however, this to be untrue: engine size and fuel type are recorded for vehicles belonging to households that participated in the survey, alongside distance data for personal travel which includes use of those vehicles by individuals within households. This would have allowed Bonilla to gain access to better information for his study.

Even more recent research that uses the NTS for plug-in vehicle research in the UK, conducted after the initial write-up of this thesis, use the statistical summaries only [180, 183, 184]. Only one study [185] appears to have used the full NTS, although explanation of how is not provided. The second author of that paper (and friend to this author), Sikai Huang, is now looking to further use the NTS with more rigorous investigation. Huang previously used the UK Time of Use Survey (UKTUS) to gather information about travel behaviour for plug-in vehicle load profiling [186] but realised the limits of the UKTUS for these purposes.

The UKTUS is another people-focused survey but the descriptions for the subject categories for the NTS and UKTUS by the UK Data Service, highlight the difference in focus of each, and thus their relative suitability for plug-in vehicle travel behaviour modelling. Subject categories for the UKTUS are listed [187] as 'employment and labour', 'family life and marriage - social stratification and groupings', 'social attitudes and behaviour - society and culture' and 'time use - society and culture'. Whereas the NTS has only one subject category [188]: 'travel and transport'.

The UKTUS also spans only one year (the year 2000) whereas the NTS is an ongoing national survey with information spanning many years[14] and therefore a far larger sample size,

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[13] This reference was 'in press' at time of reading.

specific to travel behaviour although the Centre for Time Use is hoping for more UKTUS to be undertaken in future years [189]. Usefulness of the UKTUS should not be dismissed however as it offers much complementary information, especially for more detailed studies of potential plug-in vehicle ownership from a social perspective, consideration of personal day-to-day activities and the impact of all these things on recharging behaviour at a local level.

Although the authors later realised the NTS is the better resource for the purpose of the research in [186], their research was still the first within the field of plug-in vehicle travel behaviour and load modelling to be based in the UK, that in the absence of access to real-life plug-in vehicle trials did not in consequence rely solely upon statistical summaries for national government surveys, but instead directly consulted a social database. This example needs to be followed.

4.4 CHAPTER 4 SUMMARY

Literature reviewed in this chapter highlighted the potential benefits of switching road transport to electricity dependency, if loads are managed and scheduled carefully. This complements the findings from the quantitative well-to-wheel analysis conducted earlier in this chapter that fossil fuel dependency could be reduced by such a switch. Although the use of fossil fuel dependency parameters in well-to-wheel assessments have not been used before, the very basic method outlined here is a good starting point for addressing the need to refocus research away from symptoms and back to root causes. Specifically, bringing back the focus of energy use in the UK from emissions to what should be the primary motivation for changing energy pathways in the UK: reduction and eventual cessation of dependency on a non-renewable resource – one for which we have far higher priority needs as chemical feedstock (medicines, food distribution, road infrastructure, clothing, building materials, fertilisers etc) than as a source, carrier and store of energy.

The implications of fossil fuel efficiency parameters to consider the compound well-to-tank and tank-to-wheel requirements for energy of road transport highlight the need for further research into the relative balances of energy efficiency versus fossil fuel use. It was interesting to see that on its own, the provision of electricity is very energy – particularly very fossil fuel energy – intensive. It was even more interesting to see that there is obviously a threshold for vehicle energy use efficiency that could counterbalance that part of the energy pathway for road transport and enable plug-in vehicles to reduce overall fossil fuel consumption although real-life relative differences between energy usage of plug-in versus conventional vehicles is another complication that needs further investigation than performed here.

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[14] The 2002-2008 dataset was used for this thesis.

Literature suggests great potential for both beneficial and harmful impacts arising from the uptake of plug-in vehicles, regarding their interactions with the electricity generation and supply network. Whilst research into future benefits continues to snowball, however, little research has been done investigating the intermediate stage where plug-in vehicles are being adopted but there is no advanced smart grid facilitating the monitoring and control mechanisms needed for demand management of recharging. Nevertheless, the general consensus is that unrestricted recharging will likely cause problems. There has also been no attempt at consumer-based estimation of potential numbers for plug-in vehicles and the travel behaviour of such vehicles has not been investigated as thoroughly as it could be.

CHAPTER 5: ANALYSIS OF PLUG-IN VEHICLES ENTERING UK MARKETS

Fig. 5.1. Summary of specifications of interest gathered from plug-in vehicle manufacturers for this chapter. To see how this information will relate to following chapters, see Fig. 1.1 in Chapter 1.

This chapter covers the collection of vehicle specifications necessary to determine vehicle ownership and to construct plug-in vehicle recharging profiles (when combined with findings from the next two chapters: Chapter 6 and Chapter 7) in Chapter 8, see Fig. 5.1. For an overview of how the chapters tie together see Fig. 1.1 in Chapter 1. The necessary information was gathered from a variety of sources detailed in this chapter.

The reasons behind why specific vehicles have been chosen is also provided, along with a list of specifications of interest explaining in brief how these will be used in later work. Specifications for chosen vehicles are provided, with note given to how some specifications have changed over time. Lastly, specifications are compiled to create a standard BEV and PHEV to be used later in the assessment of vehicle ownership statistics and the establishment of national recharging profiles.

5.1 BACKGROUND TO VEHICLE SPECIFICATIONS RESEARCH

This part of Chapter 5 briefly covers the sources of specifications used in the study, reasoning behind the study's focus upon four-wheeled domestic plug-in vehicles and lists which specifications in particular were of interest to the study and why.

5.1.1 SOURCES OF SPECIFICATIONS

During the period of time where specifications for plug-in vehicles were being researched, there were many constraints on information available. Academic papers at the time cited vehicle specifications for older vehicle designs that did not represent those presently being unveiled by manufacturers. The start of the study coincided with a sudden interest in plug-in vehicles by automotive manufacturers across the world, spurring technological advances that appeared to be progressing at a far greater rate than academic research – which requires additional time for study, writing and publishing purposes – could keep up with. The primary sources of information on specifications were the vehicle manufacturers themselves.

Websites for popular car manufacturers marketing vehicles in the UK were searched for availability and/or advertisement of plug-in models. This process was aided by reviewing websites such as www.thegreencarwebsite.co.uk and www.nextgreencar.com that regularly report news on new plug-in models and list those presently or imminently available in the UK. Nearly all manufacturers had or were producing concept designs for such vehicles, but only manufacturers who appeared to be lining up plug-in models for mass-sale were further investigated. Specifications were then collected from their websites and whenever information was lacking, correspondence with the administrators of manufacturer-run *fan pages* on Facebook was used. Interestingly, all maintained a Facebook presence.

It should be noted that specifications changed and continue to change over time, sometimes with the creation and disbanding[15] of 'minisites' for vehicles as information moved from international to country-specific manufacturer websites. The figures used in this study will already have been outdated by the time the first draft of this thesis was complete. This can be partly attributed to slight tweaks in actual specifications by manufacturers e.g. weight reduction leading to increased mileage range prior to sales release of vehicles, but changes can also reflect modifications made in light of their customer's feedback testing vehicles in real-life scenarios.

It should also be noted however that for example different manufacturers test their vehicles' effective mileage ranges using different methods that in turn yield different results. This in turn

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[15] The tendency for vehicle manufacturer websites to change frequently has made referencing very difficult. The references listed for this chapter are predominantly those that are available at time of writing because many that were the source of information at time of use are now unavailable. It was deemed more useful to provide references that can direct the reader to the appropriate vehicle site rather than to hyperlinks that no longer function and have not been 'cached' by search engines like Google.

makes comparisons between vehicles from different manufacturers difficult. Until an international unification of these standards is adopted by all manufacturers, the only way to assess differences would be to individually test the different vehicles by a given means – an option not available for this study.

5.1.2 CHOICE OF VEHICLES

Plug-in vehicles are not new to UK roads. Example: for many years dairies around the UK relied upon electric milk floats to deliver milk from doorstep to doorstep. As noted by www.nextgreencar.com (one of several websites that list the sorts of plug-in vehicles available for purchase in the UK) however:

> *"Although electric vehicles have been available for decades, only recently have the major manufacturers invested in high quality electric models to meet the needs of twenty-first century. This has involved increasing driving range and reducing vehicle price. A new recharging infrastructure is also being rapidly developed across the UK.*
>
> *While a number of specialist companies had already developed small electric city cars (which are actually legally classed as 'quadricycles') – including the Reva G-WIZ micro-car and the MEGA City – more recently, mainstream auto makers are now offering proper electric cars, with most of the major manufacturers likely to follow suit in the next two years."*

- Next Greencar website, from 'Electric Car buying guide' at [190]

Some models such as the Mitsubish iMiEV, were being trialled as police cars [191] around the UK and other European countries. Several iMiEV also received impromptu field-testing after the March 11th 2011 earthquake and tsunami in Japan as disaster relief emergency vehicles (see Fig. 5.2). These vehicles proved themselves not only to be capable of handling far more rugged conditions than one might expect an ordinary vehicle to face, but also incredibly useful in this scenario where fuel delivery and storage was curtailed but much of the electricity delivery infrastructure remained intact.

The vehicles whose specifications were used in this study were as follows: for PHEV: General Motor's (Chevrolet) Volt, General Motors/OPEL/Vauxhall's Ampera and Toyota's (plug-in) Prius. For BEV: Nissan's LEAF, Renault's Fluence, Mitsubishi's iMiEV, Citroën's C-Zero and Pergeot's iOn. It should be noted that the Volt and Ampera use the same drive chain and aside from aesthetic differences and differences in price and payment methods, are very similar vehicles. A similar comparison can be made between the iMiEV, C-Zero and iOn.

Fig. 5.2. A Mitsubishi iMiEV delivering disaster relief to disaster struck areas of Japan following the Tohoku earthquake of March 11th 2011. Photo provided by the official 'Mitsubishi i-MiEV Electric Car in the UK' Facebook page - www.facebook.com/imiev. More information about this and other electric cars used in disaster relief efforts at the time can be found in [192].

All of the vehicles listed above are targeted for sale on the mass market as electric equivalents to small four-door vehicles suitable for family households. Thus the sample does not entirely reflect the number of plug-in vehicles available. There are already electric scooters and electric bicycles, many of which can be recharged at home and are increasingly popular. Electric motorbikes are also in development. Initially there was concern for the lack of other types of vehicles included in this sample used in the study but this concern was set aside for several reasons explained henceforth.

There is very little information with which to make estimates of bicycles – plug-in or traditional. It is difficult to find a way to scale up use of such vehicles in the NTS [1] to national figures of ownership and travel behaviour. This is because there is no requirement for bicycle users to hold a licence for ownership or to ride on UK roads. The lack of national ownership data provides reason enough to exclude bicycles from this study. Meanwhile concerning motorbikes and scooters, there are national records for numbers of various different kinds of four-wheeled vehicles, motorbikes and scooters based on licensing information. The chosen modes of transport in the UK are however predominantly those for four-wheeled vehicles, namely cars [7, 17]. The study was thus limited to four-wheeled plug-in cars.

Another reason for the study's focus on four-wheeled cars was that different kinds of ownership were assumed to affect the likelihood of a given vehicle being replaced by a plug-in vehicle substitute, but different ownership types (e.g. private car, company car) in the NTS [1] are only listed for four-wheeled vehicles. It was assumed for this study that plug-in vehicles were unlikely to be provided to employees as company vehicles for three reasons:

a) A company vehicles is often provided when an employee's job involves a lot of driving, or involves the carrying of large and/or heavy goods,
b) Employers will be concerned with keeping costs down – first purchase prices for plug-in vehicles are higher than their conventional counterparts and the employer may or may not reap the benefits of fuel cost reductions,
c) Plug-in vehicles returned to the employer will need recharging facilities on-site.

The higher price of plug-in vehicles versus conventional vehicles, their lower mileage range, their lower energy storage capacities that lead to a requirement for more frequent 'refuelling' and their need for a recharging infrastructure to be provided on-site when not assigned to an employee, were assumed to be disincentives for their purchase by employers as company cars. These factors may not always remain disincentives and indeed Renault was planning to market (and now has) an all-electric van – the Kangoo from its Zero Emission range – for business use [193] but specifications for the Kangoo were lacking at the time.

Lastly, vehicles investigated were constrained by the data available in the NTS [1]. The vehicles recorded in the NTS are those used by members of households, not companies and their employees. So the sample includes a smaller proportion of commercial vehicles than exists in reality as many commercial vehicles are stored on-site, not at employees' homes. All things considered it seemed more and more sensible to abandon inclusion of commercial vehicles. Finally, the NTS lists ownership criteria only for four-wheeled vehicles, so to incorporate ownership into the assessment of vehicles listed in the NTS for suitability to be replaced with plug-in vehicle substitutes meant abandoning anything but four-wheeled vehicles for the study.

5.1.3 SPECIFICATIONS OF INTEREST TO THIS STUDY

There are six plug-in vehicle specifications of interest to this study:

- Price
- Mileage range
- Battery capacity
- Recharging duration
- Rate of recharging
- Recharging method

These specifications are required to answer the questions of how many BEV versus PHEV to include in later scenarios (assessing ownership), what assumptions can be made about how much energy they require from recharging and for how long (constructing recharging profiles) and what technology exists to facilitate recharge scheduling.

5.1.3.1 Specifications for ownership

Carley et al. [194] found price to be the foremost barrier to ownership, as perceived by potential consumers in the USA, with mileage range being the second greatest concern. The plug-in vehicle ownership criteria chosen to be applied to the NTS database [1] later in the NTS statistics extraction method (Part 1) were therefore assumed to be prices of vehicles and their mileage ranges. Average prices were calculated – these would then set an arbitrary limit based on consultation of personal finances for a representative individual. The average mileage range for PHEV and BEV was calculated so as to be used to distinguish between PHEV and BEV eligible vehicles and those that could be substituted with neither. Once ownership is established in Chapter 6 the subsequent ratio can be scaled up to form national estimates for numbers of BEV and PHEV.

5.1.3.2 Specifications for recharging load profiles

For the construction of scenarios however it was decided that an example BEV and an example PHEV should be chosen to later represent the two populations, with specifications available at the time. This was deemed the best course of action as specifications varied not only between vehicles but changed over time and when the study first began some vehicles had more information than others.

The number of BEV and PHEV estimated from the assessment of ownership, having also identified travel behaviour for each including daily mileages and recharge windows (time between last return to and first departure from home), can then form the basis for the construction of recharging profiles. Additional specifications to be used in constructing recharging load profiles for this study include recharging rates and durations and battery capacity – the percentage of which can be used based on the assumption that a full battery equates to a given number of miles travel in a linear relationship.

Details for rates of recharging were not included in plug-in vehicle specifications from manufacturers; therefore in later work recharging rates were calculated for the chosen standard vehicles by dividing their battery capacities by the hours taken for a flat-to-full recharge. This assumed that time taken to recharge was directly proportional to the percentage State Of Charge (SOC) of the battery that needed to be recuperated.

5.1.3.3 Specifications relating to the possibility of recharge scheduling

A further feature of interest for this study was how different plug-in vehicles might be set to recharge at specific times. It was assumed that if most vehicles were trending towards having a timer that could be set for recharging, then timers could be used to enable recharge scheduling. If vehicles did not have a timer, scheduling would rely solely on an owner's willingness to physically plug in the vehicle and set it to recharge at a specified time, with willingness being dependent upon other conveniences besides the need for adequate recharging to conduct the next day's travel.

5.2 LIST OF SPECIFICATIONS COLLECTED FOR CHOSEN VEHICLES

This part of Chapter 5 documents research into the specifications gathered for the vehicles chosen in this study. It notes where possible how these specifications have changed during the course of the study. Recharging rates were not collected as figures were not available, but they will be calculated in the next part of this chapter ready for use in subsequent chapters.

5.2.1 PRICE

Plug-in vehicles are generally noted as being more expensive to purchase than their fuelled counterparts and that this is a noted deterrent for interested buyers [113]. In the UK, government incentives have been put in place to reduce the first-cost burden of plug-in vehicles to encourage purchase by means of a plug-in car grant:

> *"Since January 2011, motorists purchasing a qualifying ultra-low emission car can receive a grant of 25 per cent towards the cost of the vehicle, up to a maximum of £5,000."*
>
> - DfT, from 'Plug-in Car Grant Guidance' online at [195]

This is in addition to funding to aid the construction of necessary recharging infrastructure up and down the country, focusing on cities [141]. As of 30th September 2012, 2311 claims have been made through the Plug-in Car Grant scheme [195]. The cars eligible for the Plug-in Car Grant at time of writing were:

- Chevrolet Volt
- Citroën C-Zero
- Mia
- Mitsubishi i-MiEV
- Nissan Leaf
- Peugeot iOn

- Renault Fluence ZE
- SmartFortwo electric drive
- Toyota Prius Plug-in Hybrid
- Vauxhall Ampera

Note: At the time research was originally conducted there was little information available about the Mia and the SmartFortwo is a two seater – not a family – car, so both these models were excluded from the remainder of the study. Discussed below are prices for the vehicles that were included in the study, allowing for a comparison to be made between the prices given in 2011 and the prices given in 2012. It can also be noted that there has been a shift in the assumed style of ownership for some BEV.

Both Table 5-1 and Table 5-2 show the full prices as of plug-in vehicles before and after the government incentive was applied. 2011 prices are provided in Table 5-1, 2012 prices are provided in Table 5-2. By 2012 some manufacturers expected customers to pay per month or consider a lease option, rather than have the option for an up-front single payment, e.g. the Citroën C-Zero has a four-year 40,000 mile contract for £249 per month excluding VAT, which leases both the vehicle and its battery pack with different warranties for the vehicle and its drive train [204]. The Peugeot iOn is available for lease from £249 per month plus VAT [205].

Table 5-1: Prices for plug-in vehicles with reference to possible sale in the UK, as collected during March 2011.

Vehicle manufacturer	Model	Type	Pre-incentive price (£)	Price after incentive (£)
Nissan	LEAF	**BEV**	23390	18390
Renault	Fluence		32160	27160
Mitsubishi	iMiEV		28990	23990
Citroën	C-Zero		19920	14920
Peugeot	iOn		19920	14920
General Motors (Chevrolet)	Volt	**PHEV**	Unknown	Unknown
Vauxhall/Opel	Ampera		Unknown	Unknown
Toyota	Prius		Unknown	Unknown

Prices for BEV were acquired from the Nissan UK website [98] for the Nissan LEAF, converted from Euros as it was displayed at the time into GBP on the Renault website [196] for the Renault Fluence and from [197] for the Mitsubishi iMiEV. Prices gathered for the Peugeot iOn came from the Peugeot iOn minisite which is no longer available and from [198] for the Citroën C-Zero.

Table 5-2: Prices for plug-in vehicles with reference to possible sale in the UK, as collected during July 2012.

Vehicle manufacturer	Model	Type	Pre-incentive price (£)	Price after incentive (£)
Nissan	LEAF	**BEV**	30990	25990
Renault	Fluence		(not reported on website)	17495 + 76/month battery lease including VAT
Mitsubishi	iMiEV		28990	23990
General Motors (Chevrolet)	Volt	**PHEV**	34995	29995
Vauxhall/Opel	Ampera		34995	29995
Toyota	Prius		32895	27895
Prices for BEV were acquired from [98] for the Nissan LEAF, from [199] for the Renault Fluence and from [200] for the Mitsubishi iMiEV. Prices for PHEV were acquired from [201] for the Chevrolet Volt, from [202] for the Vauxhall Ampera and from [203] for the Toyota Prius.				

The Nissan LEAF had a notable increase in price from £18,390 to £25,990 but upon searching for a reason why, details were hard to find but impacts of the earthquake and tsunami of 11th March 2011 were downplayed and it was proposed that the manufacturer simply "increased the content and the value of the vehicle" [206]. The Mitsubishi iMiEV stayed the same but its sister vehicles – the iOn and C-Zero – adopted alternative payment methods and warranties. The Renault Fluence was the only vehicle to drop in price, but also adopted a change in payment method through battery leasing.

5.2.2 MILEAGE RANGE

Table 5-3 shows a snapshot of the mileage ranges of the vehicles of interest as they were in the year 2010. At that point in the study, little or no information was available on PHEV. Table 5-4 shows the mileage ranges as stated for vehicles of interest in 2011. It was these mileages that would be used to generate the average mileage used to determine which vehicles in the NTS were replaceable with BEV and PHEV.

At the time, there was very little evidence from real-world users of plug-in vehicles to lend credence or criticism to these figures so they were taken as given. There is however, now that owners of plug-in vehicles have had time to test their vehicles, presently some considerable criticism of for example the range claims for the Nissan LEAF [207]. Early references for BEV – the Nissan LEAF, Mitsubishi iMiEV and Renault Fluence – stated that these vehicles were tested on NEDC cycles. According to the Renault Fluence brochure:

Table 5-3: Mileage specifications for plug-in vehicles (BEV only, PHEV specifications available) with reference to possible sale in the UK, as collected during August 2010.

Vehicle manufacturer	Model	Maximum range (mi)
Nissan	LEAF	100
Renault	Fluence	100
Mitsubishi	iMiEV	80
Citroën	C-Zero	80
Peugeot	iOn	80
Specifications for the Nissan LEAF were acquired from [98], from [196] for the Renault Fluence, from [200] for the Mitsubishi iMiEV and [204] for the Citroen C-Zero. Specifications for the Peugeot iOn were unavailable at the time, so it was assumed that the iOn would have the same mileage range as the Citroën C-Zero and iMiEV.		

Table 5-4: Mileage specifications for plug-in vehicles with reference to possible sale in the UK, as collected during March 2011.

Type	Vehicle manufacturer	Model	Maximum range (mi)
BEV	Nissan	LEAF	109
	Renault	Fluence	115
	Mitsubishi	iMiEV	93
	Citroën	C-Zero	93
	Peugeot	iOn	93
PHEV	General Motors (Chevrolet)	Volt	AER of 50, total: 370
	Vauxhall/Opel	Ampera	AER of 25-50, total: 360
	Toyota	Prius	AER of 14.3, total unknown but website stated it would be “hundreds of miles more”
Specifications for BEV were acquired from [98] for the Nissan LEAF, from [199] for the Renault Fluence, from [200] for the Mitsubishi iMiEV, from [204] for the Citroën C-Zero and from [205] for the Peugeot iOn. Specifications for PHEV were acquired from [201] for the Chevrolet Volt, from [202] for the Vauxhall Ampera and from [203] for the Toyota Prius.			

> *“NEDC (New European Driving Cycle) is a standard European measurement of emissions and consumption based on a rolling road test. It is the same standard for petrol and diesel engines as it is for electric cars. It is an objective way to measure the performance gaps between competition models. The car is on a rolling road, undertaking the same urban cycle (ECE-15 cycle) three times, then the extra-urban cycle once. The average of these 4 cycles decides the NEDC range.”*
>
> - Renault, from Renault ZE brochure available at [208]

The NEDC is criticised as having a far less strenuous pattern of testing than other cycles. It is suggested that potential buyers consider the maximum range of plug-in vehicles when considering possible longer distance driving [194], but that in the context of longer distance driving which is usually conducted at higher speeds on motorways, NEDC figures for maximum mileage range of plug-in vehicles may be incorrect.

At time of writing some figures appear to have changed yet again and references reflect the changes made by manufacturers. Toyota have increased the AER (All Electric Range) of their plug-in Prius to 15 miles whilst official advertisement of the mileage range of the Renault Fluence is now only available in the brochure (although it remains 115 miles). General Motors now quote 300 miles for the non AER range of their Volt, giving a total range of 350 miles, bringing it in line with the Vauxhall Ampera as would be expected.

5.2.3 BATTERY CAPACITY

Battery capacities have remained unchanged for the vehicles of interest in this study up until early 2012 – these figures were collected in 2011 but were rechecked against manufacturer information in July 2012. For the PHEV considered in this study, capacities were as follows:

- General Motors (Chevrolet) Volt – 16 kWh, from website [201]
- General Motors/OPEL/Vauxhall Ampera – 16 kWh, from brochure [209]

The battery capacity of the Toyota (plug-in Prius) was unknown at the time research was gathered. Note the Volt no longer has battery capacity listed in its specifications, but is assumed to be identical to its sister, the Vauxhall Ampera. Battery capacities for the BEV considered in this study were as follows:

- Nissan LEAF – 24 kWh, from website [98]
- Renault Fluence – 22 kWh, from brochure [208]
- Mitsubishi iMiEV – 16 kWh, from website [200]
- Citroën C-Zero – 16 kWh, from website [204]
- Pergeot's iOn – 16 kWh, from brochure [210]

All batteries were stated as being Li-ion. It is assumed that other differences between batteries, along with differences in vehicle mass, must exist to explain the relative differences in miles per unit battery capacity between the different vehicles from by different manufacturers.

5.2.4 RECHARGING DURATION

Rates of recharging changed over time for different vehicles, as did specifications for how these vehicles were expected to be charged. Initially home wall sockets were expected to be used when recharging at home, with possible faster recharging rates available from specified recharging points in the envisioned EV recharging network. Table 5-5 lists the recharging times quoted by manufacturers in March 2011.

Table 5-5: Recharging specifications for plug-in vehicles with reference to possible sale in the UK, as collected during March 2011.

Type	Vehicle manufacturer	Model	Home	Fast
BEV	Nissan	LEAF	7h at 230 V UK, but this was given as 10 h by the admin of the Facebook fanpage	80% full in 0.5 h
	Renault	Fluence	6-8h at 10 A or 16 A, 220 V	0.5 h at 32 A 400 V
	Mitsubishi	iMiEV	6h at 240 V UK	*[no information provided]*
	Citroën	C-Zero	6h at 220 V	80% full in 0.5h at 50 kvA, 400 V
	Peugeot	iOn	7h at 220 V or 240 V AC	80% full in 0.5h at 330 V DC
PHEV	General Motors (Chevrolet)	Volt	Under 3h at 230 V (UK) – equivalent to 37 miles	*[No information provided]*
	Vauxhall/Opel	Ampera	Just over 4 h at 240V 13A UK	*[No information provided]*
	Toyota	Prius	3h at 110 V AC	1.5 h at 220 V AC

Times for BEV were acquired from [98] and personal correspondence with the Nissan LEAF facebook fanpage (www.facebook.com/nissanleaf) for the Nissan LEAF, from [199] for the Renault Fluence, from [200] for the Mitsubishi iMiEV, from [198] for the C-Zero and from the Peugeot minisite that is no longer available for the Peugeot iOn.

Times for PHEV were acquired from [201] for the Chevrolet Volt, from [211] for the Vauxhall Ampera and from [203] for the Toyota Prius.

As can be noted from the table, manufacturers had different approaches to tackling the question of recharging durations and made different assumptions about the local distribution networks that would be used. Over the time of the project, the recharging times tended to fluctuate between 6-8 h for BEV and 3-4 h for PHEV.

The Renault Fluence was the first BEV to advocate the use of a home recharging box, which in the case of the Renault Fluence included the timer as well as reduced recharging duration. The Nissan LEAF has adopted a similar idea, although the timer is still built into the car. Table 5-6 provides the recharge durations as given for the same plug-in vehicles in July 2012.

Table 5-6: Recharging specifications for plug-in vehicles with reference to possible sale in the UK, as collected during July 2012.

Type	Manufacturer	Model	Home	Other	Fast
BEV	Nissan	LEAF	Home recharging unit: 8 h "faster charging performance thanks to a permanent 16 A current supply".	Via 10 A cable to public recharging stations: 12 h.	Leaf-compatible DC flat to 80% full in under 30 minutes, dependent upon ambient temperature.
	Renault	Fluence	At home in standard charging mode: 6-9 h depending on the available power.	*[No longer mentioned]*	*[No longer mentioned]*
	Mitsubishi	iMiEV	7-8 h.	*[No information provided]*	Flat to 80% full in under 30 minutes.
	Citroën	C-Zero	7 h at 220 V 13 A.	*[No information provided]*	Flat to 80% full in under 30 minutes from a terminal delivering monophase 125 A.
	Peugeot	iOn	7 h 220 V AC.	*[No information provided]*	Flat to 80% at 330 V AC.
PHEV	General Motors (Chevrolet)	Volt	6 h at 230 V or 4 h from the optional home charging station.	*[No information provided]*	*[No information provided]*
	Vauxhall/Opel	Ampera	6 h at 240 V 10 A.	*[No information provided]*	*[No information provided]*
	Toyota	Prius	"Plug it in at home, the office, or an on-street charging point for just 90 minutes" – equivalent to 15.5 miles.	*[No information provided]*	*[No information provided]*

Times for BEV were acquired from [98] for the Nissan LEAF, from [208] for the Renault Fluence, from [200] and from the brochure downloadable from the same site for the Mitsubishi iMiEV, from [204] for the Citroën C-Zero and from the brochure for prices and specifications [210] for the Peugeot iOn.

Times for PHEV were acquired from [201] for the Chevrolet Volt, from [202] for the Vauxhall Ampera and from the brochure downloadable from [203] for the Toyota Prius.

5.2.5 RECHARGING METHOD

As noted in the previous section, many BEV are now moving towards the requirement for a special 'wall box' to be installed at home for recharging. In the case of the Renault Fluence at the time the information was being used, this box was assumed mandatory and to contain a timer for recharging. Presently Renault have teamed up with British Gas for the installation of a dedicated wall box regardless of the need – home or commercial, single or multiple vehicles. Also British Gas launched an Off Peak Saver tariff complemented by the option of spreading the cost of a dedicated home charging solution over 12 months with a British Gas Payment Plan.

The Nissan LEAF includes an on-board timer that the driver can programme both in the car and remotely via a smart phone interface [212]. Onstar RemoteLink is an app available for Cadillac, Chevrolet, Buick and GMC owners with a 2010-2012 model year eligible vehicle and enables use of mobile devices to access real-time data from their vehicles and perform commands [213]. In the case of the Chevrolet Volt this includes viewing battery SOC, AER remaining and control of charging and charge mode settings.

There has been no mention of a recharge timer being installed for Mitsubish iMiEV, Citroën C-Zero or Peugeot iOn, but correspondence with the official Mitsubishi iMiEV fanpage on Facebook (www.facebook.com/iMiEV.official) confirmed that future models would likely include means to set a timer for recharging. The Toyota Plug-in Prius appears to have a similar arrangement with Scottish Gas and British Gas companies for the installation of wall boxes for recharging according to the UK brochure [214]. The international website suggests that the Entune smart phone app, compatible with the Toyota Plug-in Prius 'Advanced' model, can allow users to view their pre-set recharge start time and to tell the vehicle to start recharging remotely by overriding the vehicle's charge timer, implying that it has a timer [215].

At time of writing, there were 720 plug-in vehicle charging locations in the UK, according to [216]. Nissan have implemented a scheme for LEAF owners whereby they provide fast recharging points at many of their dealerships around the UK [217]. It worth noting however that although there was a "record low" in numbers of fuel stations for conventional vehicles in the UK in 2009, this still amounted to 9013 stations [218]. Compare this against the number of plug-in vehicle recharging points and note that recharging plug-in vehicles may require, per vehicle, upwards of 30 minutes to be plugged in before relinquishing the recharging point for use by another vehicle. The conservative assumption was thus applied in this study that at-home recharging was to be the default option for plug-in vehicles.

5.3 CREATING A STANDARD BEV AND PHEV

In an ideal model, all kinds of plug-in vehicles and all households across the nation would be assessed for compatibility to determine possible numbers of plug-in vehicles and also their distribution. Within the limits of this study, far more simplistic assessments will be made and so just two kinds of plug-in vehicles will be considered: a PHEV and a BEV. A standard will be derived in this part of Chapter 5 whose specifications are to be used later.

Vehicles specifications provided in this chapter needed to be used in two different ways going forwards with the study. In the first stage (NTS statistics extraction method – Part 1), mileage specifications and prices were needed to assess how many vehicles in the NTS were replaceable with PHEV and BEV. The next stage (NTS statistics extraction method – Part 2) of the study would use recharging duration specifications and calculated recharging rates for PHEV and BEV in order to construct national demand profiles for each. So, slightly different specifications were used for these two different purposes. It was assumed a recharge timer would be available for both the PHEV and the BEV.

5.3.1 SPECIFICATIONS TO BE USED LATER FOR BEV

Specifications used in the NTS extraction method (next chapter) Part 1 are listed under ‘Specifications for ownership’. Specifications used in the NTS extraction method (next chapter) Part 2 are listed under ‘Specifications for recharging load construction’ and were those of the Nissan Leaf.

5.3.1.1 Specifications for ownership

New cars are often sold with payment packages that see the vehicle bought ‘on finance’ over several years, with often the addition of a significant amount of interest [219]. According to statistics from Alliance & Leicester, people borrow on average 9,000 when they buy a new car [220]. The average price for BEV in March 2011 was £19,876 after the full plug-in car grant was applied. If this figure were split into 4 years of monthly payments, the monthly payment would amount to around £414. Minus the £9000 presumed paid upfront from the loan, the payment towards the car would then be around £226, plus an unknown amount of interest plus the loan repayments again with an unknown amount of interest.

Representative personal finances indicate that a couple earning £23,000/a prior to tax etc. would almost certainly be unable to afford a vehicle with a cost breakdown as above. An increase of earnings to £30,500/a however would have pushed take-home pay over the necessary threshold to be able to afford a vehicle at that price. Adding interest payments on top would have also added to the need for increased earnings although by how much was unknown.

As will be explained in Chapter 6, household incomes are banded in the National Travel Survey (NTS). The bands were initially too broad to be fit for use in this way but consultation with NTS staff enabled the division of household incomes into finer bands, specifically there were two bands at that range of income (£30,000 – £34,999 and £35,000 – £39,999). So a household income of £35,000/a was assumed to be a conservative minimum prerequisite for a household to own a plug-in vehicle (lower income households were excluded).

The average maximum mileage range for BEV in March 2012 was 100.6 miles. For ownership criteria this figure was assumed to be the maximum mileage travelled on any day of the week by a BEV owner, with the assumption that they could only recharge their vehicles at home.

5.3.1.2 Specifications for recharging load construction

The Nissan LEAF was deemed the best example BEV at the time the specifications were used for the study. Nissan's manufacturing centre in Japan had been hit hard by the March 11th tsunami triggered by the earthquake on the same day in 2011, but the factory for the production of the LEAF was based in the UK and sales began as scheduled that year. The vehicle had the largest battery capacity (24kWh) and the largest mileage range (109 miles) second only to the Renault Fluence which boasted a smaller battery capacity but at time of writing has yet to be launched for sale in the UK. Correspondence with the Nissan LEAF Facebook fanpage clarified that the recharge time for the UK should be more like 10 h, so this was the figure used. A flat-to-full recharge time of 10 h and a battery capacity of 24 kWh, assuming a linear recharging rate implied the rate should equal 2.4 kW/h.

5.3.2 SPECIFICATIONS TO BE USED LATER FOR PHEV

Specifications used in the NTS extraction method (next chapter) Part 1 are listed under 'Specifications for ownership'. Specifications used in the NTS extraction method (next chapter) Part 2 are listed under 'Specifications for recharging load construction' and are for the Vauxhall Ampera.

5.3.2.1 Specifications for ownership

As noted prices for PHEV were unavailable at the time specifications were being collected, so were assumed to be either equivalent or higher than those recorded for BEV and so the same assumptions for prerequisite household income were made. The average maximum mileage potential on a full battery and full fuel tank for PHEV considered in this study was 365 miles, with an average AER of 33.9 miles. The maximum AER of any PHEV listed in this study was 50 miles. It was always assumed that PHEV would be preferred by customers who required longer distance driving than those interested in BEV. If it is assumed that for sake of convenience recharging is not an option for vehicles travelling longer distances but a single fuel top-up is, then these figures can be used as threshold values for ownership of PHEV.

The government advises that for every 2hrs spent driving, drivers should take a 15 minute break [221] – that's 140 miles travelled on a motorway travelling at the speed limit of 70 mph. This is well above the AER of the PHEV considered for this study, it is however just under twice the combined (AER plus fuelled range) distance the average PHEV could travel. If stopping for fuel and rest is considered an inconvenience then such a PHEV could travel a maximum of 365 miles with just one rest break. If the driver stops roughly 2hrs into their journey and tops up the fuel tank, they can expect the vehicle to travel an additional 90 miles, bringing them to a maximum journey length of 455 miles without stopping other than to rest at journey's end. If two rest stops are incorporated 2 hrs apart and both involve refuelling, then the PHEV could have a maximum of 545 miles.

For comparison it was noted that the Toyota Prius – the standard non-plug-in version – was able with a 45 litre fuel tank capacity and 3.9 litres per 100 kilometre fuel efficiency, to travel over 716 miles before running out and requiring refuelling. All things considered, the maximum range of a PHEV used to determine ownership was arbitrarily set to 500 miles.

5.3.2.2 Specifications for recharging load construction

The Vauxhall Ampera was deemed to be the best example PHEV at the time specifications were gathered for use in the study. At the time specifications were needed, Toyota appeared to be having second thoughts about making a plug-in Prius and there was little push for advertisement in the UK. Meanwhile the Ampera was being positioned as the European cousin to the Volt, for which most detailed information at the time came from the American websites, aimed at American consumers.

The Ampera information was UK focused, so it was hoped that specifications for the vehicles recharging needs would be the most accurate of the PHEV. So, with a battery capacity of 16 kWh, taking 4 h to recharge from flat to full, a recharging rate of 4.2 kW/h was assumed for PHEV in the construction of recharging load profiles the study. The AER of the PHEV is irrelevant[16] to the later construction of load profiles but is assumed here to be the maximum possible for the Ampera: 50 miles.

5.4 CHAPTER 5 SUMMARY

Plug-in vehicles expected to be marketed in the UK were reviewed. Price and mileage range specifications that were translatable into parameters for ownership of PHEV and BEV eligible vehicles in National Travel Survey (NTS) [1], were collected. Averages were taken for both as (see Fig. 5.3) and these will next be used in the NTS statistics extraction method (Part 1) in Chapter 6, as simplistic models for selecting vehicle records from the NTS based on the ownership criteria: household income, and maximum daily mileage travelled. Average prices for BEV were assumed to represent also PHEV prices, because prices for PHEV were unknown at the time the figures needed to be used in this study. Assumptions for maximum daily mileages for PHEV were made based on government-recommended driving habits and UK speed limits.

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[16] PHEV AER is irrelevant because as will be subsequently explained in Chapter 8, even when the assumed AER is that of maximum listed for the Ampera (or any PHEV whose specifications were investigated in this chapter) of 50 miles, that AER would be significantly less than any mileage a PHEV would be expected to travel on any day of the test week. This means that in all scenarios designs constructed in Chapter 8, it was assumed PHEV would require a flat-to-full recharge.

BEV – Assumed specifications (averages)

Price: £19876

Range: 100.6 mi

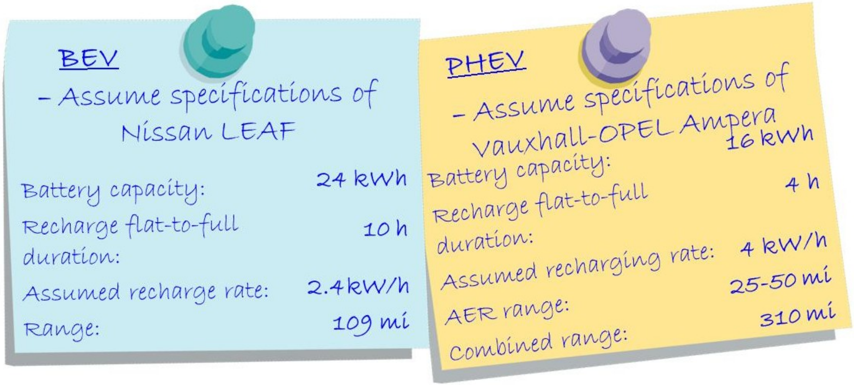
PHEV – Assumed specifications (averages)

Price: [assumed to be equivalent to BEV or higher]

Combined range: 500.0 mi

Fig. 5.3 Vehicle specifications applied as criteria for identifying BEV and PHEV eligible vehicles to construct plug-in vehicle ownership estimates in Chapter 6.

The Nissan Leaf and Vauxhall-OPEL Ampera were chosen as the test vehicles for subsequent load modelling of BEV and PHEV populations respectively, once average behavioural patterns were established in Chapter 6. Specifications used for load modelling are described in Fig. 5.4, where recharging rate was assumed to be the battery capacity divided by the time required to recharge those vehicles batteries from flat-to-full.



BEV
– Assume specifications of Nissan LEAF

Battery capacity: 24 kWh

Recharge flat-to-full duration: 10 h

Assumed recharge rate: 2.4 kW/h

Range: 109 mi

PHEV
– Assume specifications of Vauxhall-OPEL Ampera

Battery capacity: 16 kWh

Recharge flat-to-full duration: 4 h

Assumed recharging rate: 4 kW/h

AER range: 25-50 mi

Combined range: 310 mi

Fig. 5.4 Vehicle specifications assumed in the construction of plug-in vehicle recharging profiles in Chapter 8.

CHAPTER 6: PLUG-IN VEHICLE OWNERSHIP AND TRAVEL BEHAVIOUR

One of the major contributions of this thesis is the NTS statistics extraction method outlined in this chapter. This is a method for establishing population size estimates at a national scale for plug-in vehicle ownership as based on people factors, not electricity supply system limits or government policies on emissions reduction for road transport.

Over the past three to four years growing interest in vehicle usage and travel has increased the availability of statistics specific to vehicle usage. A large number of studies in the USA have begun to utilise the National Household Travel Survey [222] for vehicle energy use assessments [223], modelling loads [224] and considering plug-in vehicle recharging impacts on e.g. transformer aging [225].

Fig. 6.1. Summary of statistics of interest gathered from the National Travel Survey [1] for this chapter. To see how this information will relate to following chapters, see Fig. 1.1.

Presented here is the only publicly documented method for extracting vehicle-focused statistics from the UK equivalent to the American NHTS: the people-focused National Travel Survey (NTS) [1]. The NTS is the largest and most comprehensive nationwide survey of travel behaviour in the UK, for which previously only summary statistics obtained from the Department for Transport's website have been used by researchers in this field. Fig. 6.1 introduces the key statistics that can be garnered from the NTS [1] (on the left of the diagram) and the questions that will be posed here to select statistics for plug-in eligible vehicles.

In this study a simple case is considered where the nation is assumed to have only two types of plug-in vehicle, one being a BEV, the other a PHEV. For reasons subsequently explained, it has been assumed that these vehicles recharge at home only. Before plug-in vehicle recharging loads can be constructed, however, three questions must be answered (refer back to primary research questions 1 and 3 outlined in Chapter 1):

- How many are there of each type of vehicle?
- What are the average first departure from and last return to home times of these vehicles?
- What are their maximum and average daily mileages for each day of the week and thus expected vehicle energy usage and potential recharging requirement per day of the week?

Fig. 6.2 outlines the method of extracting vehicle-focused statistics from the NTS that will provide the necessary answers to these questions. To answer the first question an assessment of likely ownership is required, scaled up to a national estimate as per the first part of the NTS statistics extraction method, documented in this chapter. To answer the second and third questions requires an assessment of the travel behaviour of those vehicles eligible for replacement with BEV and PHEV as identified by the answer of the first question. That assessment of travel behaviour is covered by the second part of the NTS statistics extraction method, documented in this chapter.

As can be seen in Fig. 6.2 there is a third part to the NTS statistics extraction method documented in this chapter: the gathering of supplementary statistical and graphical information about vehicle use across the two selected populations (vehicles eligible for replacement with BEV and vehicles eligible for replacement with PHEV). This is to help inform the interpretation of results in Chapter 9, from scenarios constructed in Chapter 8, which use the statistics produced in parts 1 and 2 of the NTS statistics extraction method in this chapter. This is a necessary step for anyone seeking to use the NTS for the purposes envisioned in this thesis, because it enables whatever the model or simulation subsequently based on the statistics extracted from the NTS by this method to be used in the context of its limitations.

All work investigating the NTS was done using Microsoft Access 2007, with some supplementary work done using Microsoft Excel 2007.

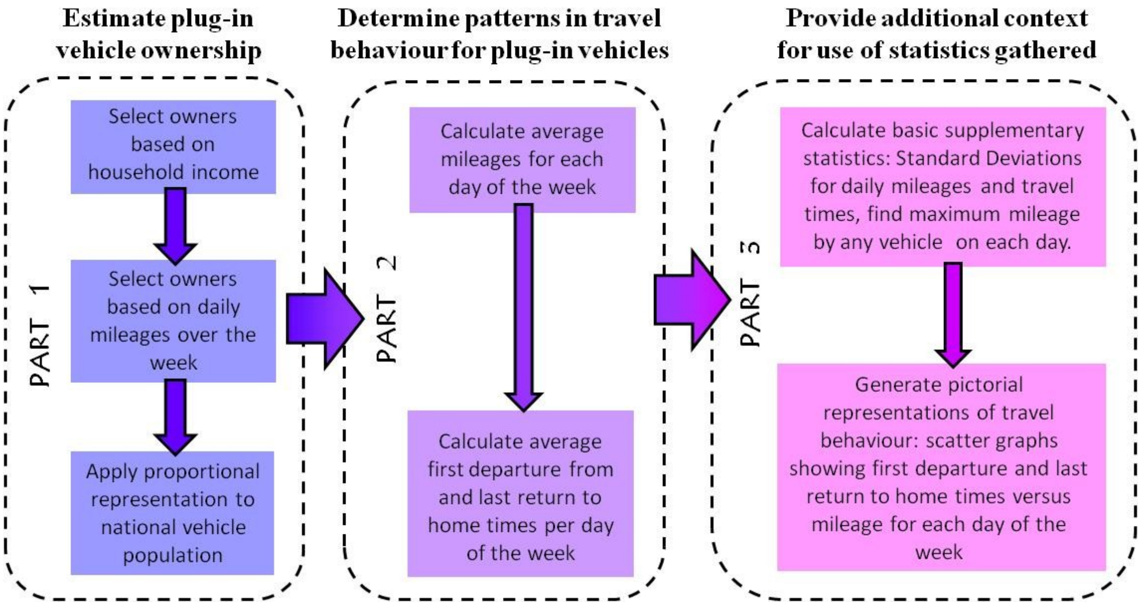


Fig. 6.2. Overview of the NTS statistics extraction method debuted in this thesis whereby vehicle-focused statistics are extracted from a people-focused data source: the NTS [1]. The arrow joining the two text boxes in Part 3 is to emphasise that in the method, it is wise to conduct the tasks in that order due to process requirements. The upper process in Part 3 requires minimal work to be done to the outputs of Part 2, but the lower process in Part 3 required a substantial amount of additional work to be carried out in order to complete.

6.1 NTS STATISTICS EXTRACTION METHOD PART 1: ESTIMATING PLUG-IN VEHICLE POPULATION SIZE BY OWNERSHIP CRITERIA

A summary of Part 1 of the NTS statistics extraction method documented here is provided in Fig. 6.3 but a far more in-depth documentation of the actual process, complete with screen shots for reference to specific stages is provided in Appendix 1. Part 1 is broken down into three sections (A, B and C). Firstly, Vehicles are selected based on the incomes of the associated households that own them (section A). Secondly, vehicle-relevant information that allows travel records to be used to distinguish between vehicles that are eligible for replacement (with a BEV, PHEV or neither) based on maximum daily mileages travelled on any day of the week, are pulled together (section B). Thirdly, the number of vehicles found to be eligible for replacement with BEV or PHEV was scaled up to national estimates (section C).

Not all criteria of interest in this study can be located in one file, so several files had to be linked together to gather the information required. Due to the larger file size of the NTS, this included a long series of record selections conducted one after the other in a series of steps, eliminating records prior to bringing in additional information as the process continued.

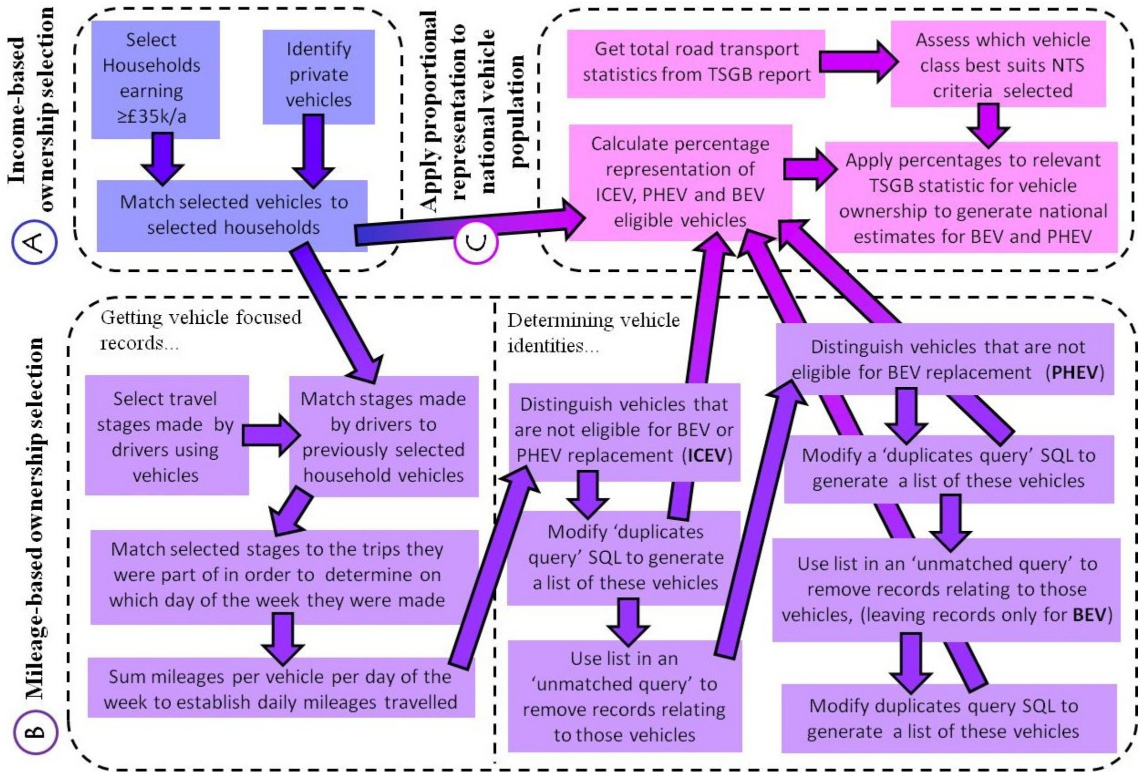


Fig. 6.3 Breakdown of Part 1 of the NTS statistics extraction method, consisting of three sections. Reference in section C is made to the use of the Transport Statistics Great Britain (TSGB) report 2009 edition [7].

6.1.1 SECTION A: SELECTING VEHICLES BASED ON HOUSEHOLD INCOMES

There were three steps involved in selecting vehicles based on household incomes. Firstly, households had to be selected for fully participating in the NTS [1], and supplementary household income bandings had to be acquired from the NTS team at the Department for Transport to enable the selection of households with incomes of £35,000 per year (shorthand: £35k/a) or more. Secondly, vehicles needed to be selected based on their type of ownership (e.g. private, or company car) so that it could more legitimately be assumed that the households using those vehicles were themselves in charge of purchasing replacements, therefore that household income could be assumed to relate to ownership. This included the additional process of correcting for an oversight in NTS coding whereby the Vehicle and Stage files had mismatched criteria for identifying different vehicles in use by the same household. Selected vehicles and selected households then had to be matched up.

The NTS [1] provides statistics on household income, not disposable household income (income after the subtraction of must-be-paid items such as mortgage, heating bills, food). So, household income, not disposable household income, had to be used in this study as a proxy for incorporating the role of vehicle price in BEV and PHEV ownership. Following on from the assumptions built in Chapter 5, ownership of any plug-in vehicles – BEV or PHEV – based on income was set at a household having a minimum income of £35k/a.

Realistically, factors for ownership of plug-in vehicles are highly complex [108] and so plenty more work could be done to refine this income-based selection of plug-in vehicles incorporating an additional new stage to consider those factors. Only a simplistic method for incorporating decisions on thresholds for income into assessing plug-in vehicle ownership is presented in this thesis.

The vehicle ownership criteria that were applied in this study excluded vehicles in use by households that were company cars – with fuel part, full or not paid for by companies – that were not belonging to the self-employed. Self-employed people were assumed to have a greater personal say over the type of vehicle they used and an income-based perspective for vehicle-ownership. Also excluded were non-four-wheeled vehicles, because ownership type is not listed in the NTS for any vehicles other than those with four wheels. The reasoning behind the exclusion of company-owned vehicles is as follows:

- It was assumed ownership and therefore choice of vehicle type was determined by the company and not the household to whom a company vehicle was registered, so household income would not function as a proxy for plug-in vehicle ownership for those vehicles
- Company vehicles could include a number of vehicles that for a variety of reasons might not be suitable for replacement with plug-in types (such as lorries and smaller vehicles expected to be used similarly for long-distance driving or the transport or numerous/heavy goods)
- More generally: to match up the types of vehicle and ownership that could be distinguished in the NTS [1] to the types of plug-in vehicles coming to UK markets for which specifications were readily available during the investigations carried out in Chapter 5

There was little point, after all, in including the travel records of vehicles for which specifications of plug-in vehicle alternatives were unavailable, or vice versa in investigating other plug-in vehicle types in Chapter 5 that could not be distinguished from other unwanted types of vehicles (or ownership) in the NTS [1], or for whom the vehicles they might substitute (e.g. standard bicycles) have no registered form of ownership and thus whose population sizes could not be scoped.

6.1.2 SECTION B: SELECTING VEHICLES BASED ON DAILY MILEAGES

Initial processing was required first of all to sum for each vehicle the total mileages travelled per day of the week. A more complicated series of steps had to be taken because the day of the week on which a trip was made is only listed under criteria in the Trips file, whilst criteria detailing the length in miles of a particular stage and more importantly whom (which household person) made a given journey, is listed in the Stage file. The latter issue is of particular importance because as noted many times in this thesis, the NTS [1] is people (not vehicle) focused. Another issue is that journeys are listed for passengers as well as drivers so long as those passengers are members of the household. Unless passenger journeys are removed, duplication of journey information will distort summed daily mileages.

So, Stages were selected based on their belonging to drivers, then based on their belonging to the household vehicles of interest, then these were matched to Trips files to allow mileages to be summed per day of the week. Daily mileages used to determine which vehicles could be substituted with a BEV, PHEV or neither were as previously stated in Chapter 5:

- BEV = vehicles whose summed mileage on any day totalled 100.6 miles or less
- PHEV = vehicles whose summed mileage on one day or more was more than 100.6 miles, but no greater than 500.0 miles on any day
- ICEV (non-plug-in vehicles excluded from further study) = any vehicle whose summed mileage on any day exceeded 500.0 miles

Although listed in this order, the selection process had to be carried out in reverse, in order of decreasing assumed maximum daily mileage range. First vehicles whose daily mileages made them ineligible for replacement with BEV or PHEV (therefore remaining as ICEV) were identified and removed. Then PHEV – because they travel the longer distances than BEV – were distinguished from the records of the remaining vehicles. Removal of travel records for PHEV eligible vehicles therefore left records belonging to BEV eligible vehicles. A statistical summary of the findings of the plug-in vehicle ownership analysis of the NTS [1] is provided in Fig. 6.4. Lists were made of the number of vehicles belonging to each of these three groups so that their numbers and proportional representation of the vehicle population could be calculated in the next section.

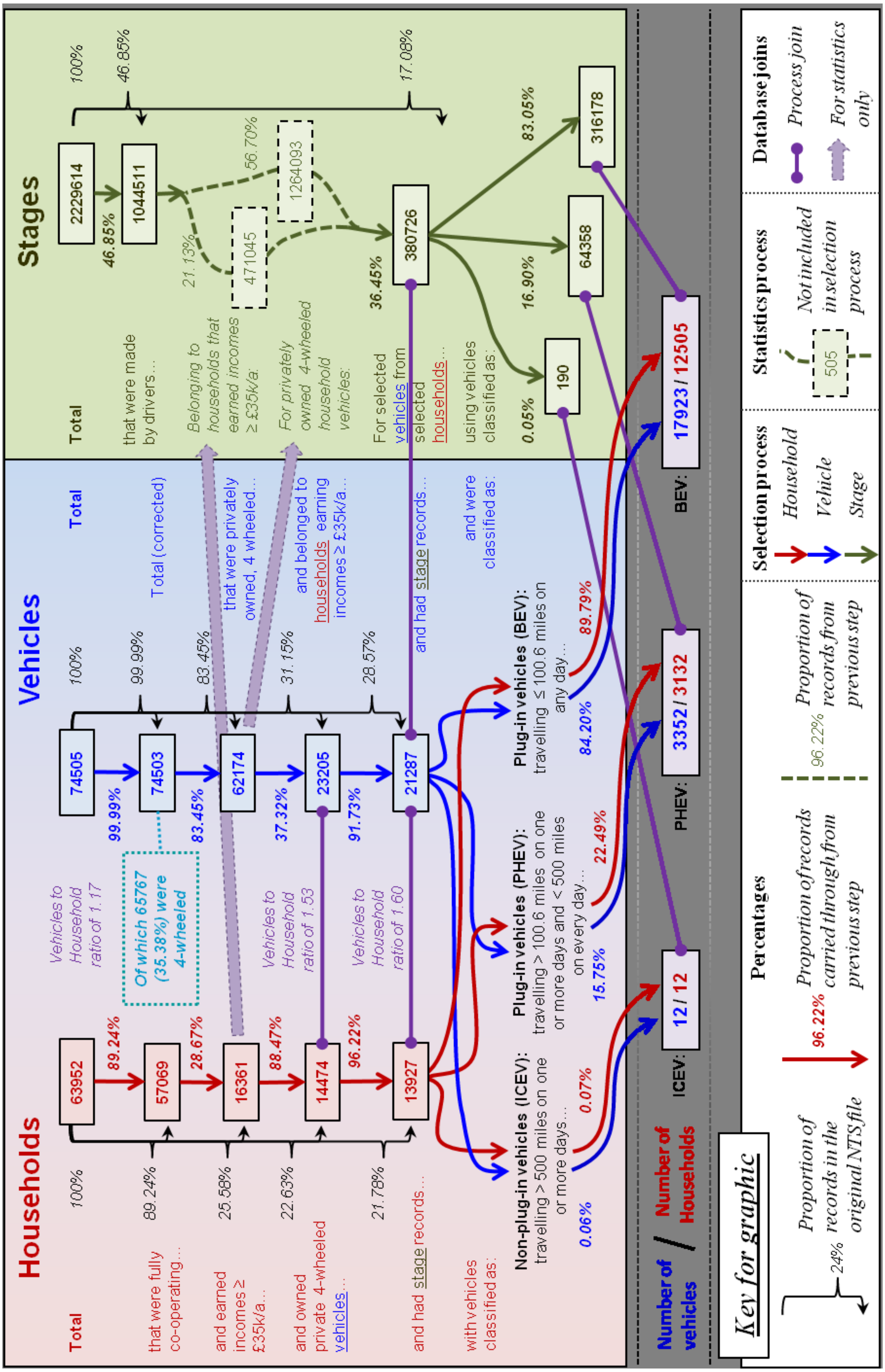


Fig. 6.4. Summary of the findings from the plug-in vehicle ownership analysis of the NTS [1] using methods described in this chapter and a summary of the key parts of the method in flow-chart form.

6.1.3 SECTION C: APPLY PROPORTIONAL REPRESENTATION TO NATIONAL VEHICLE POPULATION

In order to establish a national estimate for numbers of BEV and PHEV eligible vehicles, the DfT report 'Transport Statistics Great Britain 2009 Edition' (subsequently referred to as TSGB 2009 edition) [7] was consulted, because it includes figures for vehicles licensed to drive on UK roads per year. As noted in Chapter 5, ideal vehicles to substitute for plug-in vehicles are those that do not need to carry heavy goods and do not travel long distances, so commercial vehicles owned by companies are less likely than domestic vehicles to fit that bill. The NTS [1] meanwhile is focused on domestic households and their vehicles, which complements this ideal. Unfortunately the NTS ownership variables and the DVLA's ownership designation are not the same, so an approximate match was made between the two.

In the TSGB 2009 edition [7] report there are seven taxation classes for vehicles. Details are provided below along with figures for how many vehicles of each group were licensed to drive on UK roads in 2008. These are listed in Table 6-1.

Table 6-1: Explanation of taxation classes and number of vehicles falling into those classes in 2008 taken from [7].

Tax class	Description	Number of vehicles licensed to drive on UK roads in 2008
Private and light goods (PLG)	Covered almost 89 per cent of licensed vehicles in 2008, primarily consists of cars and light vans, includes other vehicles used only for private purposes.	'private cars' 27021000 'other' 3303000
Motorcycles, scooters and mopeds	Excludes tricycles which have their own tax band.	436000
Goods vehicles	Vehicles that have a gross weight of over 3.5 t and used for carrying goods.	1160000
Public transport vehicles	buses and coaches with more than eight seats (excluding the driver) used for commercial purposes. Vehicles not used for commercial purposes are licensed in the PLG tax class	111000
Crown and exempt vehicles	Vehicles exempt from vehicle excise duty e.g. vehicles driven by disabled drivers, emergency and crown vehicles and vehicles manufactured before 1973.	29000
Special vehicles group	Includes works trucks, road rollers, mobile cranes, digging machines and showman's vehicles.	56000
Other vehicles	Includes 3-wheeled cars and vans, recovery vehicles, general haulage vehicles and tricycles.	2091000

On one hand the tax bands are pliable to these considerations. 'Goods vehicles', 'public transport vehicles' and 'special vehicles' groups can be excluded because of their commercial ties, mass or the expectation that they are involved in the transport of heavy goods and/or involved in long distance driving. So too can 'motorcycles, scooters and mopeds' and 'other vehicles' groups, as only four-wheeled vehicles are have full ownership information in the NTS.

The 'crown and exempt vehicles' however includes a mix of vehicles that may or may not be likely plug-in vehicle candidates. Of emergency vehicles, fire service trucks are unlikely candidates but there have been trials of electric police cars [191]. Similarly disability is not a discerning factor for plug-in vehicle ownership and so may include vehicles that may and may not be candidates for plug-in vehicle substitution.

Note the 'PLG' (Private and Light Goods) taxation group is split into 'Private cars' and 'Other vehicles'. PLG 'private cars' is the category likely to include the most plug-in vehicle replaceable vehicles, but makes no distinction between private commercial and private personal vehicles. Nor is there any reference to where vehicles are parked (at home or at work) that might allow inference of ownership type and suitability for inclusion in estimates for this study.

The best analogy to that subset in the NTS would therefore be vehicles categorised as four-wheeled vehicles, including commercially owned and paid for four-wheeled vehicles. A new query had to be run for the NTS files with these criteria. The results of that query listed 65,767 vehicles, spread between 46,440 households. The figure for number of private vehicles included in the NTS (65,767) was then assumed to be representative of a sample taken of the 27,021,000 vehicles listed as 'private cars' under the PLG group in the TSGB 2009 edition [7]. That sample size, would represent of about 0.24% of that population.

Previously (see Fig 6.4) percentages were calculated for the proportion of BEV and PHEV eligible vehicles within the 23,205 vehicles listed in the NTS [1] that were selected for being privately owned 4-wheeled vehicles, belonging to households earning £35k/a. So, the estimated number of four-wheeled vehicles belonging to households earning ≥£35k/a that matched ideal ownership criteria in the total PLG (private cars) population for the UK in 2008 was:

$$\frac{23205}{65767} \times 27021000 = 9533996$$

Using the previous percentage calculated for the number of vehicles that were <u>not</u> eligible for replacement with a BEV or PHEV from Fig. 6.4, this would infer of the total PLG (private cars) population for the UK in the year 2008:

$0.06\% \times 9533996 = 5375$ vehicles were ineligible for replacement with BEV or PHEV

Using the previous percentage calculated for the number of vehicles eligible for replacement with a PHEV from Fig. 6.4, this would infer of the total PLG (private cars) population for the UK in the year 2008:

$15.75\% \times 9533996 = 1501290$ vehicles were eligible for replacement with a PHEV

Using the previous percentage calculated for the number of vehicles eligible for replacement with a BEV from Fig. 6.4, this would infer of the total PLG (private cars) population for the UK in the year 2008:

$84.20\% \times 9533996 = 8027332$ vehicles were eligible for replacement with a BEV

These population estimates will be used to estimate recharging loads when scenarios are constructed for testing in Chapter 8.

6.1.4 SUMMARY FOR NTS STATISTICS EXTRACTION METHOD, PART 1

In total 23,205 vehicles were identified as being private, four-wheeled vehicles belonging to households with incomes of ≥£35k/a. This was representative of 37.32% of all privately owned vehicles included in the NTS, spread across 14,474 households. Of these vehicles: 12 (0.05%) were deemed non-replaceable by plug-in vehicles, 3352 (15.75%) were deemed replaceable by PHEV only, 17,923 (84.20%) were deemed replaceable by BEV.

Having then established comparable criteria for vehicles surveyed in the NTS [1] versus taxation classes for which national population sizes are listed in the TSGB 2009 edition [7], national estimates for plug-in eligible vehicles were made. These amounted to: 8,027,332 BEV eligible vehicles, 1,501,290 PHEV eligible vehicles and 5375 vehicles that were assumed eligible for neither, out of the total 27,021,000 vehicles registered as ‘private cars’ under the private and light goods (PLG) taxation class in the TSGB 2009 edition [7] for the year 2008.

6.2 NTS STATISTICS EXTRACTION METHOD PART 2: DETERMINE PATTERNS IN TRAVEL BEHAVIOUR FOR PLUG-IN VEHICLES

A summary of Part 2 of the NTS statistics extraction method is presented in Fig. 6.5, but a far more in-depth documentation of the actual process, complete with screen shots for reference to specific stages is provided in Appendix 2. Part 2 is broken down into two sections (A and B). In section A, average mileages for each day of the week were calculated for vehicles identified in part 1 as BEV and PHEV eligible. In section B, 'first departure from' and 'last return to' home times were collected and averages again taken for each per day of the week, per plug-in eligible vehicle population.

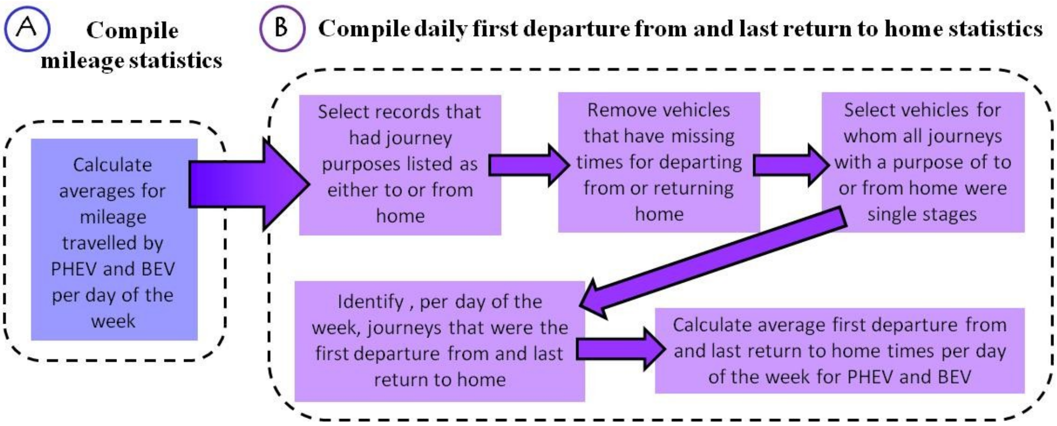


Fig. 6.5. Breakdown of Part 2 of the NTS statistics extraction method, consisting of two sections.

6.2.1 SECTION A: DAILY MILEAGES

Outputs from Part 1 of the NTS statistics extraction method were used to provide records per vehicle for mileages per day of the week for BEV and for PHEV separately. Averages for daily mileages per day of the week were then calculated.

6.2.2 SECTION B: DEPARTURE AND RETURN TIMES

Establishing first departure from and last return to home times is a necessary step if the 'recharging window' (time between returning home and leaving again the next day) open to BEV and PHEV populations is to be calculated for scenario development. In practice, this not a simple process and as shown in Fig. 6.5, was comprised of five steps. The reason for these steps is further explained later when the merits and drawbacks of using the NTS [1] are discussed, but in short: these steps arose because of the people-focus, not vehicle-focus of the NTS [1].

All travel information in the NTS is focused on individuals within households. A vehicle's first and last journey was not necessarily the same as the first and last journeys made by an individual. After returning home by car (last car journey), an individual might, for example, visit a local shop or pub on foot before returning home for the last time. Journey number and times are recorded for household members, not household vehicles. Different individuals may drive the same vehicle, so one individual's last vehicle journey, is not necessarily the last journey that vehicle made.

Were this study focused on people however, this would have been a simple task as journeys in the NTS are identified by person ID number and by order of undertaking. So, without extremely labour intensive cross-checking of records between individuals, it was impossible to determine with absolute certainty the first and last journeys made by a vehicle. If, however the following assumptions are made:

- That a journey made by an individual who was a driver,
- Using a household vehicle,
- Where that vehicle was the sole mode of transport
- ... And the vehicle stage the sole stage recorded for that journey,
- That had the journey purpose recorded as 'home'...

...Then the first or last of such journeys recorded in chronological order on a day would signify the first or last journeys of that vehicle. Also, as those would be journeys, not stages of journeys, they should also have associated start and end times within the Trip file. This is still quite an assumption to make, but it was the best alternative for the limited time available. A series of queries were run in order to collect records for vehicles based on this assumption.

First, journeys using selected vehicles with journey purposes to or from home were identified, then records were removed for any vehicles that were missing start and end time information for any of those journeys. Next, (because times are listed for journeys, not stages) journeys using vehicles to go from or to home were selected where the vehicle stage was the sole stage of a journey – in other words start and end times signify start or end times for vehicle usage.[17] Next, times for first departures from and last return to home journeys were identified per day of the week. Lastly, averages were taken for first departure from and last return to home times for the entire PHEV and BEV eligible vehicle populations.

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[17] Note: based on the aforementioned reasoning for focusing on first departure from and last return to home times, it was not necessary to have complete time information for both those journeys – only the start times for departure from home journeys and the end times for return home journeys were needed.

6.2.3 SUMMARY FOR NTS STATISTICS EXTRACTION METHOD, PART 2

Average daily mileages, per day of the week, were collected for vehicles from the NTS [1]. This was done for two populations, designated by the NTS statistics extraction method part 1 as vehicles eligible for replacement with PHEV or with BEV. Average daily mileages per day of the week are displayed in Table 6-2. Also collected in Part 2 were average times for first departure from and last return to home times for each BEV and PHEV eligible vehicles [1]. These are displayed in Table 6-3.

Table 6-2: Average mileage per day of the working week for vehicles eligible for replacement with PHEV and BEV.

Day of the week	Average mileage (mi)	
	PHEV	BEV
Monday	63.2	21.8
Tuesday	59.6	22.1
Wednesday	60.1	22.6
Thursday	63.1	22.6
Friday	73.7	22.9
Saturday	71.3	21.5
Sunday	76.7	20.7

Table 6-3: Average times per day of the working week for first departure from and last return to home for vehicles eligible for replacement with PHEV and BEV.

Day of the week	Average first departure from home time (h past midnight)		Average last return to home time (h past midnight)	
	PHEV	BEV	PHEV	BEV
Monday	09:22	09:30	17:23	17:23
Tuesday	09:16	09:28	17:31	17:31
Wednesday	09:13	09:25	17:38	17:38
Thursday	09:22	09:30	17:36	17:36
Friday	09:31	09:38	17:19	17:19
Saturday	10:56	11:10	16:20	16:20
Sunday	11:34	11:43	16:17	16:17

6.3 NTS STATISTICS EXTRACTION METHOD PART 3: PROVIDE ADDITIONAL CONTEXT FOR USE OF STATISTICS GATHERED

A summary of Part 3 of the NTS statistics extraction method documented here is provided in Fig. 6.6, but a far more in-depth documentation of the actual process, complete with screen shots for reference to specific stages is provided in Appendix 2. Part 3 is broken down into two sections (A and B).

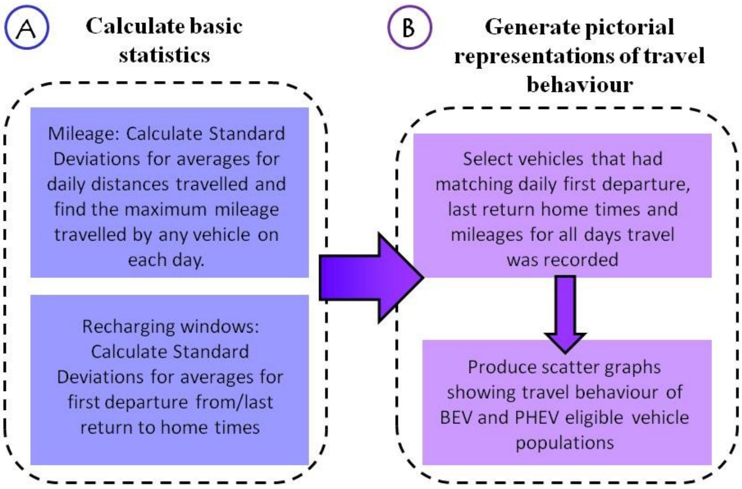


Fig. 6.6. Breakdown of Part 3 of the NTS statistics extraction method, consisting of two sections. Section A and the first step of Section B was conducted in MS Access whilst the last part of Section B was conducted in MS Excel.

In section A, supplementing the averages already calculated for mileages and times for first departure from and last return to home for BEV and PHEV eligible vehicle populations per day of the week, the standard deviation (SD) was calculated and the maximum mileage travelled by any vehicle on each day was found. In section B, in order to better show what the SD figures suggest about vehicle usage, further work was done to give a graphical representation of the distributions of vehicle travel behaviour in terms of linking mileage to times for first departures and last returns to home per day of the week.

6.3.1 SECTION A: CALCULATION OF BASIC STATISTICS

The calculation of standard deviations (SD) for averages of daily distances travelled and first departure from/last return to home times is easily made within MS Access for records within previously established queries. Similarly so, the calculation of maximum daily mileage was accomplished.

It should be noted that maximum daily mileage was a contributor to ownership criteria, and so represents an artificial cut off point for distance travelled per day. This might make the use of maximum daily mileage seem questionable but it should also be noted that at this point it is unknown if there are natural groupings between vehicles travelling on average shorter distances, as opposed to longer distances, or whether this might be affected by day of the week.

In future, this statistic or similar might be useful in further population breakdowns for BEV eligible vehicles. It is likely to be of less use to PHEV eligible vehicles however because whilst these vehicles are generally expected to be the ones travelling longer distances on each day than would be suitable to substitute with a BEV, their battery capacities are far lower than a BEV. At least from the electricity supply system's point of view, their daily distances travelled are of lesser interest if the general assumption can be made that whatever their activity, PHEV will likely fully deplete their batteries every day.

6.3.2 SECTION B: PICTORIAL REPRESENTATION OF VEHICLE TRAVEL RECORDS

Pictorial representations of vehicle travel records, relating distance travelled to times of first departure from and last return to home times per day of week are not so simple to create as the calculation of SD and other basic statistics. The first problem is that in order to construct a graph of the records, one must assume that all vehicles are leaving home and returning on the same day and therefore that there are records for both journeys. This is not the case, so in order to show how miles travelled during a particular day versus first departure from and last return to home times might relate or compare across different days of the week, only vehicles that have matching information for all three could be included in this snapshot investigation.

The second problem was the number and size of records and the processing power required to handle the data in widely available software packages such as MS Excel as intended as part of this study. Records were too numerous to be displayed in anything other than a scatter graph in MS Excel, and loading times were noticeable even when just producing cross sections of the records split by day of the week. The providers of the NTS anticipate user difficulties such as these and the NTS does actually include variables that provide banded mileages. Unfortunately the bandings used are not fit for the purposes of this study, as insufficient resolution is provided at mileages of interest for plug-in vehicle ownership thresholds. Records would have needed to be entirely re-banded to enable the production of a suitable bell curve and time allowances made this impractical.

Placing the data on a logarithmic scale for daily mileage more clearly showed the natural groupings in travel behaviour across PHEV and BEV eligible vehicle populations. More detailed statistics was deemed unnecessary in this study because what the study presents is an overview of a new method. Greater detail in statistics could be misleading if greater detail in factors affecting ownership and travel behaviour available in the NTS are not investigated first, through improvements to the whole NTS statistics extraction method presented here.

6.3.3 SUMMARY FOR NTS STATISTICS EXTRACTION METHOD, PART 3

Additional simplistic analysis has been conducted to provide context to averages calculated for mileages and times for departure from and return to home by PHEV and BEV eligible vehicles, that highlight the wider variability of human behaviour. The results of this additional analysis are presented and discussed in this summary. SD and maximum recorded daily mileages are given next to the averages for which they apply, per day of the week, in Table 6-4 for PHEV and in Table 6-5 for BEV. SD for first departure and last return to home times are provided in Table 6-6 for PHEV and Table 6-7 for BEV.

Table 6-4: Average, SD and Maximum mileage per day of the working week for PHEV eligible vehicles.

Day of the week	Average mileage (mi)	SD of mileage (mi)	Maximum mileage travelled (mi)
Monday	63.2	68.3	470.0
Tuesday	59.6	65.6	436.0
Wednesday	60.1	66.5	451.0
Thursday	63.1	69.8	445.8
Friday	73.7	73.4	421.0
Saturday	71.3	75.6	494.0
Sunday	76.7	79.0	472.0

Table 6-5: Average, SD and Maximum mileage per day of the working week for BEV eligible vehicles.

Day of the week	Average mileage (mi)	SD of mileage (mi)	Maximum mileage travelled (mi)
Monday	21.8	18.8	100.5
Tuesday	22.1	18.8	100.5
Wednesday	22.6	19.1	100.0
Thursday	22.6	18.9	100.0
Friday	22.9	19.5	100.6
Saturday	21.5	19.9	100.4
Sunday	20.7	20.2	100.6

Table 6-6: Average and SD for first departure from and last return to home times per day of the working week for PHEV eligible vehicles.

Day of the week	Average first departure (h past midnight)	SD of average first departure (h)	Average last return (h past midnight)	SD of average last return (h)
Monday	09:22	3:11	17:50	3:00
Tuesday	09:16	3:10	18:05	3:00
Wednesday	09:13	3:06	18:00	3:02
Thursday	09:22	3:10	18:02	3:12
Friday	09:31	3:08	17:42	3:15
Saturday	10:56	3:02	16:59	3:56
Sunday	11:34	3:06	16:58	3:47

Table 6-7: Average and SD for first departure from and last return to home times per day of the working week for BEV eligible vehicles.

Day of the week	Average first departure (h past midnight)	SD of average first departure (h)	Average last return (h past midnight)	SD of average last return (h)
Monday	09:30	3:06	17:23	3:04
Tuesday	09:28	3:10	17:31	3:08
Wednesday	09:25	3:09	17:38	3:08
Thursday	09:30	3:12	17:36	3:10
Friday	09:38	3:13	17:19	3:16
Saturday	11:10	3:16	16:20	3:54
Sunday	11:43	3:08	16:17	3:50

SD for both daily mileage and first departures and last return to home times were larger than the means on all days of the week. In the case of daily mileages this suggested that travel behaviour was skewed in favour of shorter journeys for both BEV and PHEV. In the case of first departures from and last returns to home, SD of around 3 h were common across both populations suggesting a great deal of variability in real life travel behaviour.

Scatter graphs are provided in Fig 6.7 for PHEV and Fig. 6.8 for BEV, showing for each day of the week: first departure from and last return to home times as plotted against mileage. The scatter graphs required a subgroup of vehicles to be taken from those selected for the calculation of averages and SD: vehicles that had appropriately matching travel information. This meant there must also be a possibility that statistics for mileage and departure/return times could be altered so as a result.

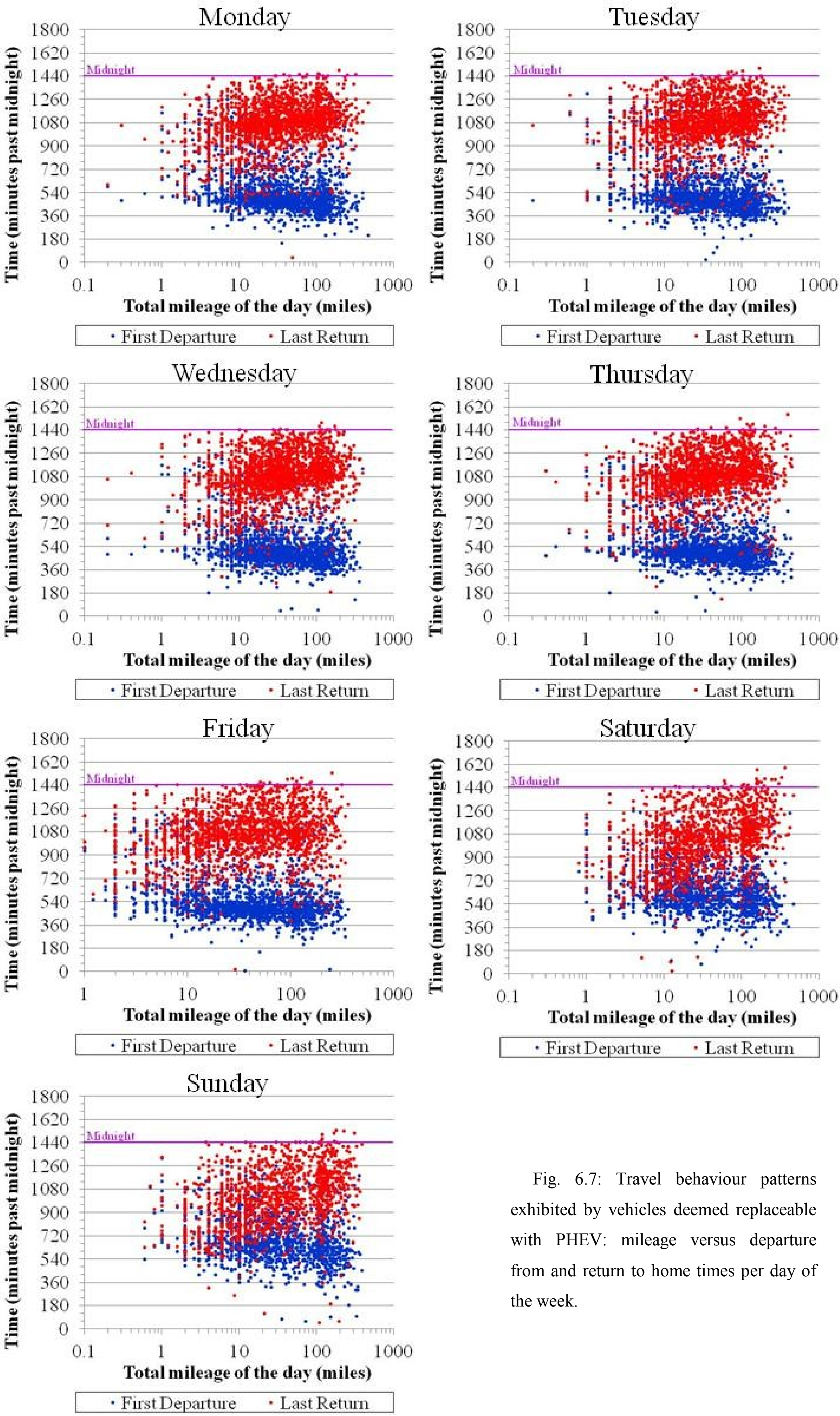
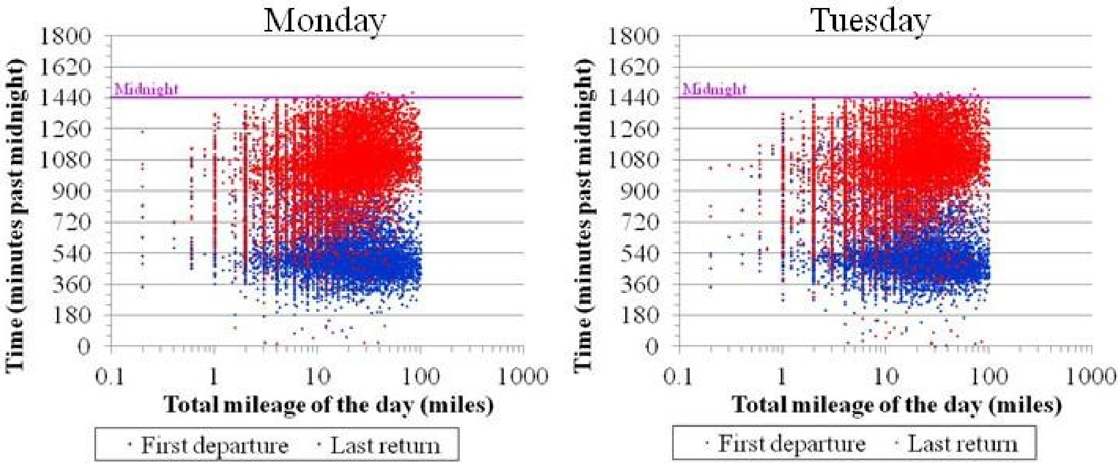
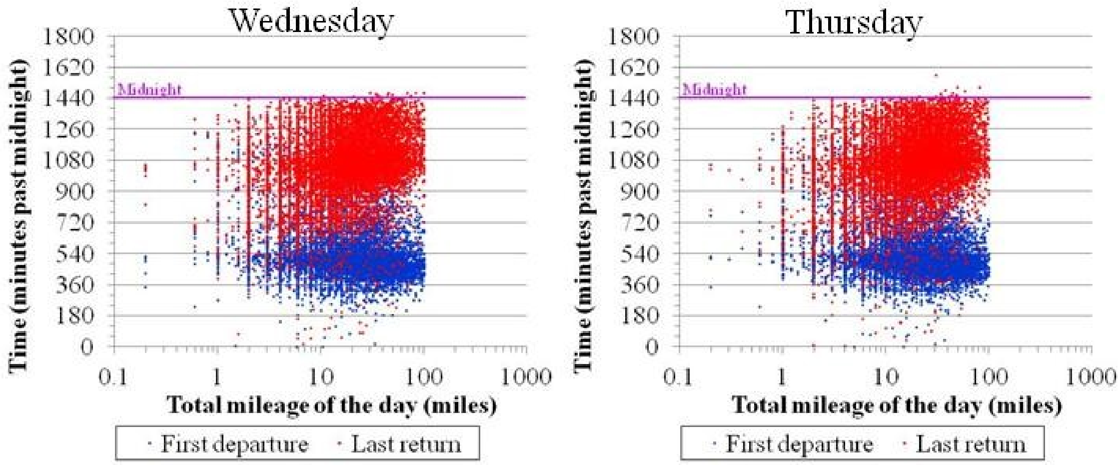
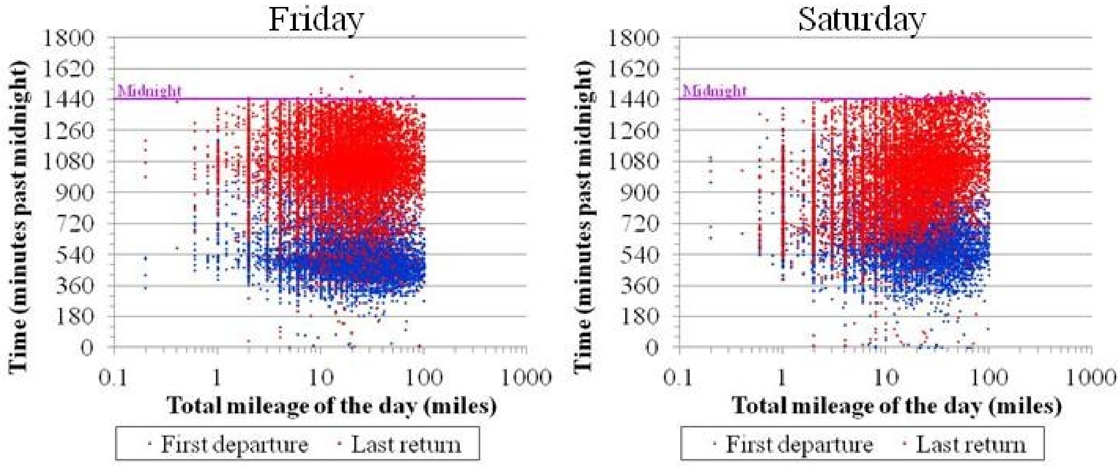


Fig. 6.7: Travel behaviour patterns exhibited by vehicles deemed replaceable with PHEV: mileage versus departure from and return to home times per day of the week.







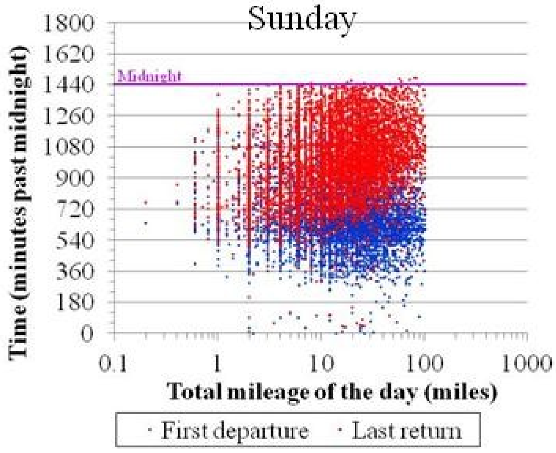


Fig. 6.8: Travel behaviour patterns exhibited by vehicles deemed replaceable with BEV: mileage versus departure from and return to home times per day of the week.

As such it should be noted that only the averages, maxima and SD previously calculated (and calculated separately) will be used in the remainder of the study. This maximises the sample size of the vehicle population for each statistic used, whilst avoiding unnecessary interference from the selection process that was required to produce the scatter graphs. A vehicle need not have any associated time information if all that is required is its daily mileage, and all information relating to distances travelled by that vehicle is complete. Similarly, a vehicle need not have complete mileage information to establish its first departure and last return times. Appendix 2 does, however, provide in Table A2-3 for PHEV and Table A2-4 for BEV the difference that could have been made to average, SD and maximum mileage per day of the working week had the vehicle sample size for mileage calculations been narrowed to that used to calculate first departure from and last return to home times.

The scatter graphs suggest that distance travelled during a day has some bearing on the times for departing from and returning home. The blue and red plots for departures and returns separate more visibly for vehicles travelling longer distances on any given day. Without further investigation to pin down how profound an influence distance may have on departure and return times, further intricacies of the relationship between the distance travelled and departure/return times was ignored. It should be recalled however, that differences between averages for travel behaviour of PHEV and BEV eligible vehicles may well reflect that relationship. PHEV eligible vehicles, selected for their longer daily mileages travelled do appear to, on average, depart earlier and return home later than BEV eligible vehicles.

Further comments may be drawn from the scatter graphs that again would require further research to confirm. The longer the distance, the longer the gap of time between departure and return, i.e. the more energy a vehicle uses during a day for travel, the smaller the recharging window may become within which that vehicle then has the opportunity to recover its battery SOC. There is also a tendency for return home times that are pushed to later times that bring about this difference, rather than departure times moved earlier.

The scatter graphs also suggest that as populations, vehicle travel behaviour appears to be more erratic on weekends than workdays with both BEV and PHEV travelling at a greater spread of times for departure and return. This may explain why average times for departures and returns are closer together (departing later, returning earlier) on weekends for both BEV and PHEV whilst average mileage on those days appears little changed (BEV eligible vehicles) or a little larger (PHEV).

One potentially interesting point to note is the visually discernible cut-off for the BEV eligible vehicle group. Both BEV and PHEV plots have centres of higher density but interestingly for BEV, the cut off for BEV eligibility falls after the density of points starts to fall away towards the higher end of mileage travelled. This indicates a natural grouping for travel behaviour between the vehicles determined by their maximum distances to be BEV eligible, versus the vehicles determined by their maximum distances to be PHEV eligible.

This is very interesting because it begs the question: did vehicle manufacturers study the NTS in order to base the mileage specifications for their vehicles – PHEV versus BEV – on these natural groupings? The answer to that question may never be known, but at least the scatter graphs do somewhat support the segregation of the vehicle population into BEV and PHEV eligible vehicles that have slightly different travel behaviour patterns as a result of ownership criteria based on the average specifications of BEV and PHEV gathered from manufacturers.

6.4 NTS STATISTICS EXTRACTION METHOD: SUMMARY AND CONCLUSIONS

A three part method has been presented here for extracting vehicle-focused statistics from a people-focused database known as the National Travel Survey [1]. The statistics gathered were:

- Estimates for BEV and PHEV eligible vehicles, which were then scaled up to national estimates for the UK using figures from the TSGB 2009 edition [7]
- Average, maximum and SD for mileages travelled per day of the week for BEV and PHEV eligible vehicles
- Average and SD for time of first departure from home per day of the week for BEV and PHEV eligible vehicles
- Average and SD for time of last return home per day of the week for BEV and PHEV eligible vehicles
- Pictorial representations of a PHEV and BEV eligible vehicle populations in the form of scatter graphs, showing first departure and last return to home times for each vehicle, versus the mileage travelled, for each day of the week.

In this basic form, these statistics are useful for the broad assessment of national impacts on electricity demand should the energy pathway that road transport relies upon be partially shifted from petroleum products to electricity. The purpose of this chapter has not been to provide in-depth analysis of the NTS [1], but rather to provide a snapshot of the NTS' as yet unexplored potential for informing policy on plug-in vehicle adoption schemes and recharging behaviour.

The statistics may be simple (average, maximum and SD only) but they reflect the simplifications made to the NTS statistics extraction method that make the method useful as a demonstrative exercise and make it more user-friendly. They also reflect the fact that the NTS itself has limitations, and there are far more factors (and vehicle types) to investigate that it may not cover due to its household and people focus.

This restriction to use of basic statistics only serves as a reminder to the user that reality is far more complex than these averages may suggest. This is made clear by the scatter graphs and should be recalled later when considering the analysis of results from scenarios constructed using these basic statistics. There are far more factors – some that may be investigable via the NTS and others that may not be – that should really be considered before exhaustive statistical analysis be conducted of travel behaviour and the results of scenarios built upon such statistics. There should be no strong declarations about likely human behaviour with regards to plug-in vehicle recharging behaviour – be they default or incentivised – until this has been done.

CHAPTER 7: ANALYSIS OF EXISTING ELECTRICITY DEMAND

Existing electricity demand needs to be investigated before any assessment can be made of the national electricity supply network's capacity to accommodate plug-in vehicle recharging loads, or how the recharging load might be modified to make it manageable. It must be determined when it is best to schedule new loads and what an ideal testing period would be (see primary research question 2 in Chapter 1). To answer that, the following just be considered:

- What is the highest magnitude of electricity demand that the supply network has accommodated without incident?
- Are there recurring patterns for peaks and lulls in existing electricity demand over the years?
- What are the timings of these?

This chapter investigates half-hourly electricity demand data supplied online by National Grid plc [8] to provide broad answers to these questions, albeit limited to national profiles and patterns of usage. Firstly, a preamble explains why the capacity of the supply system is considered at a national and not a local scale for this study. Findings from the investigation are presented and discussed in the context of what they mean for recharging plug-in vehicles, complete with a summary that draws together what information will then be used to construct recharging scenarios in Chapter 8.

The analysis presented here is a simple one – more complicated methods for demand pattern analysis can be found in Fan et al [9]. What is, however, presented here that appears to have been omitted in other literature, is a simple analysis that draws attention to the difference between maximum and minimum demand over the various well-recognised cyclical patterns progressing through the years.

Peak demand is of particular interest for planners looking to ensure security of supply for the UK's electricity system. Whether or not the system can support increased demand – be that attributed to the introduction of plug-in vehicle recharging loads or to some other new load – depends on the magnitude, duration and timing of that load, particularly in relation to existing peak demand. So, a closer investigation of patterns in peaks (and lulls) of electricity demand is warranted. Microsoft Excel 2010 was used to conduct the analysis of half-hourly electricity demand for multiple years from National Grid plc [8].

7.1 WHY NOT INVESTIGATE THE LOCALISED IMPACT OF RECHARGING

A well-known proverb states that “a chain is only as strong as its weakest link”. For the electricity supply network this would imply that research investigating the impact of plug-in vehicle recharging should focus on the capabilities of the network at a component level i.e. focus on the local, not national scale. Reality is however more complex than that.

A theoretical increase in demand at a local level may well be easily accommodated by the components along a specific distribution line without need for reinforcement, however as noted from industrial correspondence with R. Ferris, Innovation and Development Manager of Western Power Distribution, branch lines have to deal with the localised demands of several distribution lines summed together that may have very different load profiles. An increase from one distribution line could coincide with high demand from the others, exceeding the sum total demand the components of the branch line were built to cope with. So, ideally the topology of the supply network should be investigated at the component level but working across the whole system simultaneously in order to locate weak-points and identify worst case scenarios.

The national adoption of plug-in vehicles may, however, at some point reach a threshold where recharging has a national impact. There are now several studies looking at the possible impact of plug-in vehicles at isolated areas of the local distribution network including academic research e.g. [160, 226, 227] and commercial/government-led trials e.g. [148,149, 228]. Whilst there are several studies that have touched on national impacts of plug-in vehicle recharging those studies usually focus on reduction of GHG emissions and therefore ask “How many plug-in vehicles would be needed to achieve a given magnitude of GHG emissions reduction?” rather than “How many plug-in vehicles theoretically could or might be adopted by UK drivers?” – for example Papadopoulos et al. and the King Review of low-carbon cars [139, 154].

There is good reason at national scales to instead focus not on the adoption of plug-in vehicles for GHG reduction, but on how many plug-in vehicles could feasibly be taken up by consumers. Besides the fact that adoption is presently driven by market forces, not capped by regulation, there are also other reasons as to why plug-in vehicles can and are being promoted more generally regardless of GHG impacts: costly public health issues (respiratory and other problems) arise from transport associated air pollution [45, 5]. The health benefits offered by switching to plug-in vehicles are particularly well put in a paper submitted to the Journal of Epidemiology & Community Health by Sovacool in 2010 regarding PHEV:

> *"By shifting pollution from millions of individual tailpipes to power plants burning cleaner fuels with better emissions controls, as well as improving the energy efficiency of automobiles, a PHEV transition could substantially reduce incidents of cancer, asthma and lung disease and lower greenhouse gas emissions that will likely contribute to infectious disease epidemics."*

- Sovacool, page 186 from [53].

Even were there to be minimal reductions in GHG emissions from a switch to plug-in vehicles, so long as power stations – even if fossil fuelled – are located away from areas of highest population density, there will remain an argument for the switch: reducing the cost to taxpayers of public health issues (respiratory and other problems) arising from transport associated air pollution. This is effectively a demonstration of Maslow's hierarchy of needs [118] affecting prioritisation of needs at a governmental policy level, where immediate, local needs are prioritised ahead of global, long term needs.

The NTS [1], which holds information that could lend itself towards an assessment of likely plug-in vehicle uptake, complements not local scale but national scale research. It was thus reasoned that a useful contribution to this area of study would be to use people-focused – as opposed to carbon reduction focused – national data to estimate possible numbers of plug-in vehicles and then use complementary national electricity demand to consider the impact of recharging at a national scale.

7.2 INVESTIGATING HIGHEST MAGNITUDE OF ELECTRICITY DEMAND

Of the years 2002 to 2011 the highest annual demand recorded was that for Monday 17th December 2007, where demand reached 59,880 MW. Annual peak demand varies over the years – the lowest recorded being 53,344 MW in 2004 as shown by Fig. 7.1.

It should be noted that the fact that seasonal temperature changes have an impact upon annual peak demands is well-known. National Grid in their Seven Year Statements (SYS) forecast electricity demand for future years using the "Average Cold Spell" – ACS – for previous years, working then to remove the influence of temperature so as to better understand the underlying pattern of annual peak demand [229].

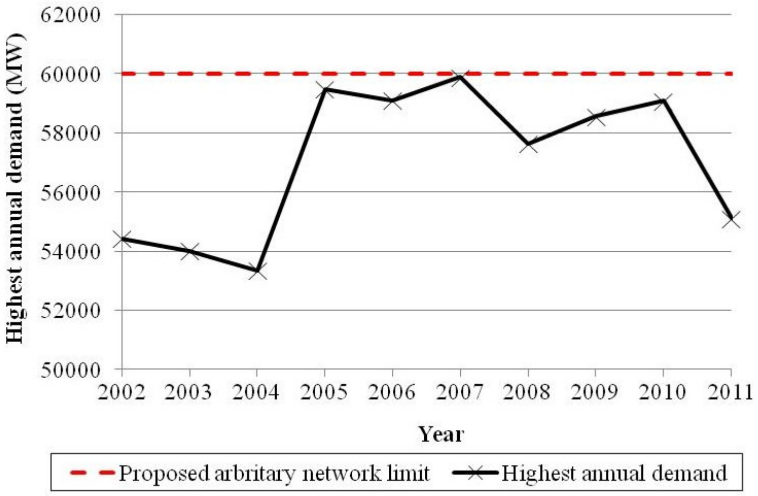


Fig. 7.1. Highest national annual demand recorded by National Grid [8] from 2002 to 2011.

The economic climate also affects national electricity usage. The 2010 SYS report states that the major factor in the decrease in demand over 2010 was the effect of the economic downturn [230]. To complicate matters these two factors – economic and environmental climates are not mutually exclusive [229]. There are also other factors that National Grid Electricity Transmission plc (NGET) considers when testing scenarios for likely future annual peak demands. In [229] the list of factors is as follows:

- Historic annual energy consumption
- Economic growth (including fuel price)
- Growth in household numbers
- Growth in industrial and commercial sectors
- Embedded generation development
- Energy efficiency measures and
- New emerging technology such as heat pumps and electric vehicles

This study does not incorporate any future forecasts of electricity demand, making mention of these factors a moot point. Their variable influence on electricity demand will not be incorporated into the scenarios in this study. Even so, it is still worth noting that these other factors that can change demand besides adding plug-in vehicle recharging exist, so as to appreciate two things:

1) That the scenarios in this study do, by default, incorporate those factors – at least in terms of their impact upon existing electricity demand as it was recorded in the years used for this study, bringing the study closer to reality.
2) That adding on plug-in vehicle demand may imply either as a requirement or as a consequence, a shift in the balance of those factors. A shift that is not modelled here and therefore leads to a departure from reality for the study.

7.3 INVESTIGATING PATTERNS IN EXISTING ELECTRICITY DEMAND

National Grid demand data [8] for Great Britain spanning from the years 2002 to 2009 was analysed using Microsoft Excel 2007 to confirm patterns in electricity usage. Data for the years 2010 and 2011 was also included in analysis of peak annual demand. Three patterns were clearly identifiable as occurring seasonally, diurnally and weekly, with interruption to these patterns occurring in coincidence with public holidays and transitions between British Winter Time (BWT) and British Summer Time (BST).

The first stage of analysis plotted all half-hourly data in the raw form supplied by National Grid [8], comparing years when displayed in cannon and when laid on top of each other. The second stage involved calculating and plotting for every day of every year in the dataset: the average, minimum and maximum demand. The difference between minimum and maximum demand was also calculated to give an idea of variability. Average, minimum, maximum and the difference between the minimum and maximum demand on each day were then plotted in cannon and also one year over another. The impact of public holidays and time changeovers was also considered.

7.3.1 SEASONAL PATTERN

When several years are laid over one another and demand compared as in Fig. 7.2 the influence of seasons is very clear. Highest annual demand always occurs in winter months, but year on year the winter peak may shift between months and the impact of the Christmas holiday period interferes with assessments by introducing a lull during winter months, confounding attempts to work out where the winter peak might naturally fall and how it may vary.

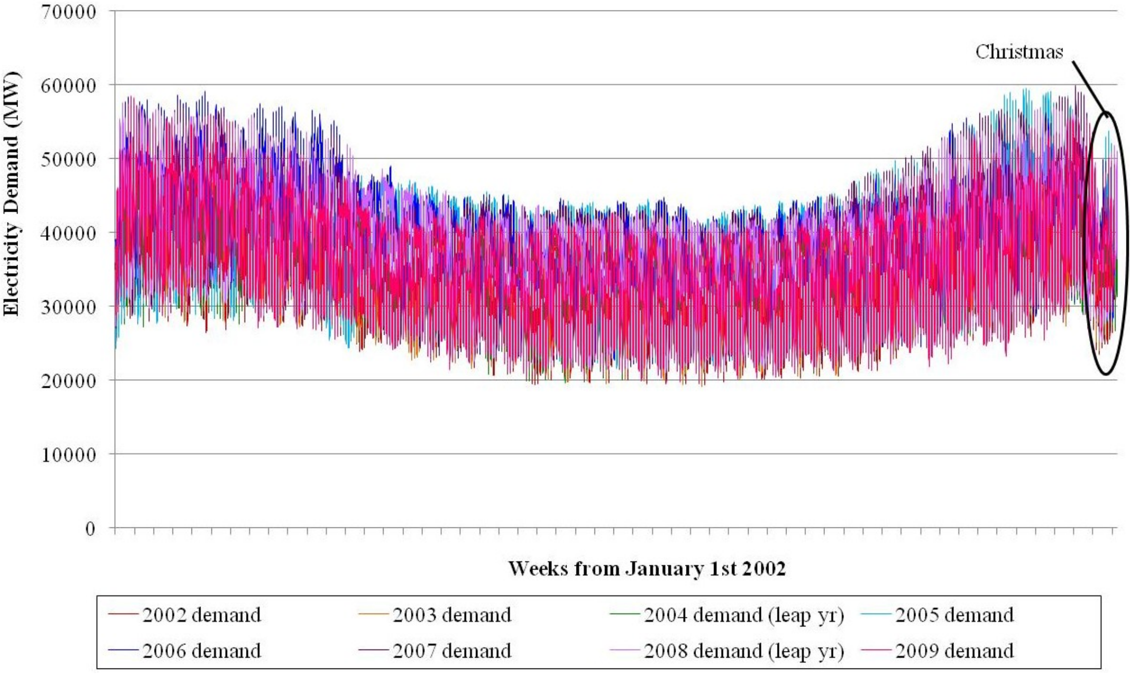


Fig. 7.2. Half hourly national electricity demand for the years 2002 to 2009 as acquired from National Grid [8]. Seasonal influence on electricity demand and the importance of the national holiday over Christmas are clearly visible.

Assessment was not made easy by the fact that years begin and end not at the transition between any two seasons but roughly in the middle of winter. Fig. 7.3 plots daily averages for all years in cannon – one after the other – and better shows how the timing of when one year ends and another begins, as well as the timing of Christmas appears to be slightly out of synch with the rotation of the seasons.

The Gregorian calendar does not model perfectly planetary movements that cause seasons and this may further confound the issue. To make matters worse, there are other things that can affect weather patterns and seasons by affecting climate, like anthropomorphic emissions and cycles in the output of the sun [59]. Seasonal patterns in electricity usage are clearly important, but the timing of seasonal peaks and lulls cannot easily be matched to a particular month for these reasons.

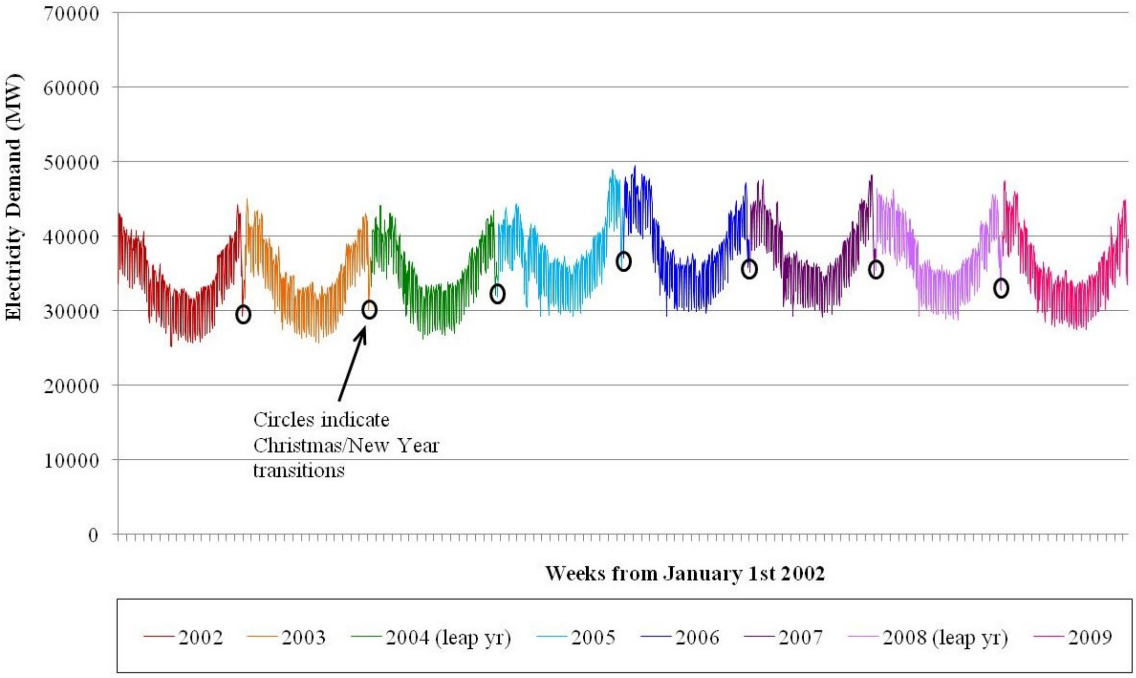


Fig. 7.3. Average daily demand for the years 2002 to 2009 in cannon, showing how the Gregorian calendar may be slightly out of synchronisation with the rotation of the seasons. Calculated using half-hourly annual data from National Grid [8].

7.3.2 DIURNAL PATTERN

Day and night transitions influence electricity demand as much as seasons do but over a far faster cycle (24 hours as opposed to 365 days). Electricity demand over 24 h periods is also predicable to a far higher accuracy than for seasons. Every day has a peak and a lull and the difference between these on any day ranges roughly between 7000 and 27,000 MW over the years. The highest annual demand can be pinned down and predicted almost to the half hour. For every year in the dataset barring 2006, the highest annual demand occurred at 17:00 h. In 2006, it occurred only half an hour later at 17:30 h.

National Grid's 2011 SYS [229] provides a breakdown of the underlying causes to the oscillation pattern seen to occur in demand over a 24 hr period. In particular related to maximum and typical weekday (workday) winter demand profiles these are quoted as being:

- 00:00h - 03:00h: Operation of time-switched and radio tele-switched storage heating & water heating equipment.
- 06:30h - 09:00h: Build-up to start of working day.
- 09:00h - 16:00h: Plateau reflecting the working day (primarily commercial & industrial demand).

- 16:30h - 17:30h: Rise to peak due to lighting load and increased domestic demand outweighing fall-off in commercial and industrial demand.

Seasons influence the shape of daily demand profiles too, as shown by Fig. 7.4, reproduced from [229]. When daily maxima and minima are plotted over the years as they are in Fig. 7.5, the importance of seasons can be further noted.

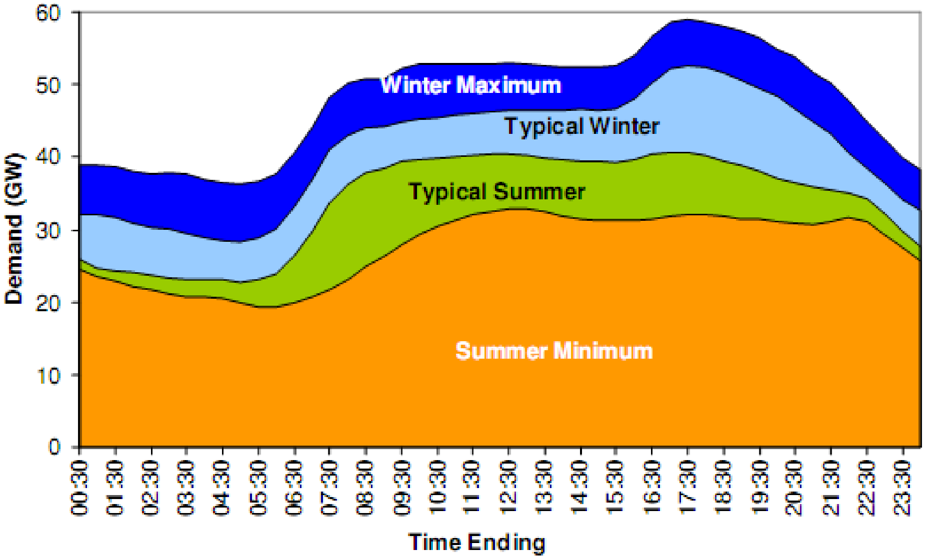


Fig. 7.4. Summer and winter daily demand profiles for 2010/11 reproduced from Fig. 2.1 of [229] – © 2011 National Grid plc, all rights reserved.

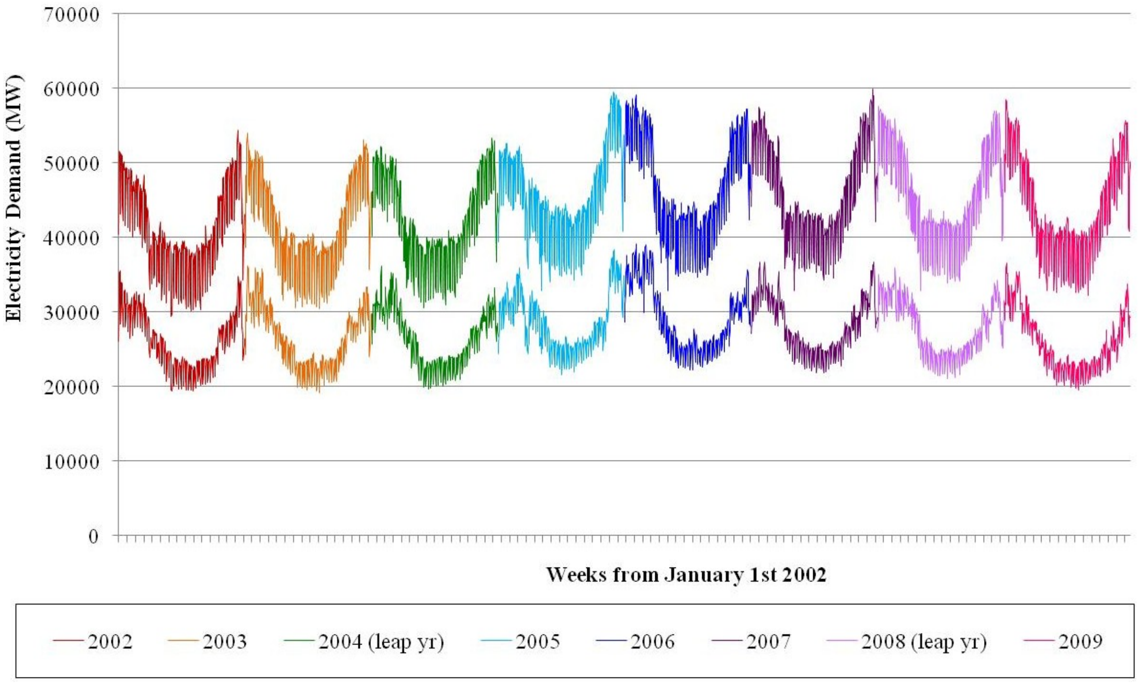


Fig. 7.5. National electricity demand plotted as daily minima and maxima plotted in cannon for the years 2002 to 2009, expressing the influence of seasons. Calculated using half-hourly annual data from National Grid [8].

The oscillations between daily maxima and minima grow larger over winter months and smaller over summer months. This is also shown by plotting how the difference between daily maxima and minima changes over the years as in Fig. 7.6. The oscillation between daily minima and maxima shown by Fig. 7.6 appears to be getting higher year on year. This is illustrated more clearly in Fig. 7.7 which plots the smallest and largest difference between daily minima and maxima for each year.

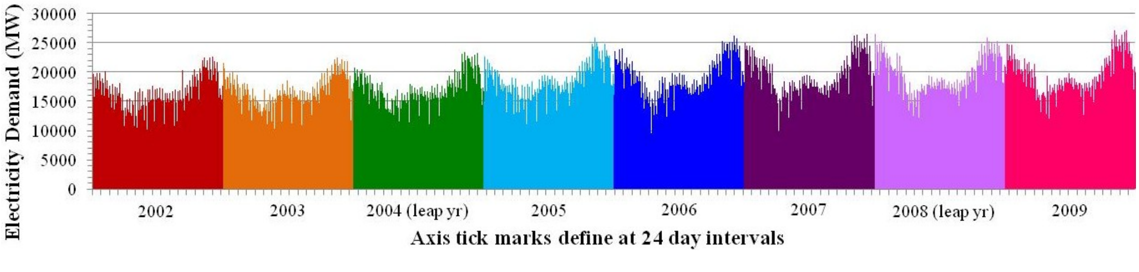


Fig. 7.6. Daily differences between minima and maxima in national electricity demand, plotted in cannon for the years 2002 to 2009, calculated using half-hourly annual data from National Grid [8]. The gap between maxima and minima is clearly influenced by seasons but there is also a slight trend towards increasing difference and the increasing influence of seasons on that difference over these years.

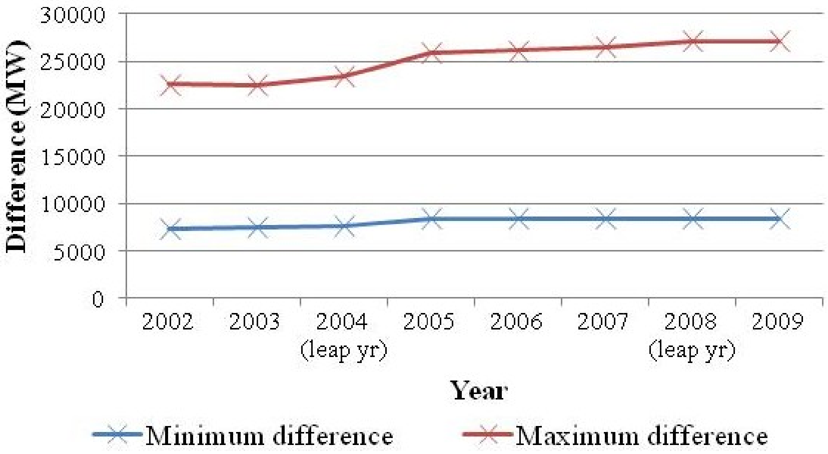


Fig. 7.7. Graph plotting per year the maximum (red) and minimum (blue) difference between daily minima and maxima as calculated using half-hourly annual data from National Grid [8]. Graph indicates a general upwards trend in the variability of demand. In every year the minimum difference occurs in summer, the maximum difference in winter, so this graph is also an indicator of upward trends in the annual difference between winter peaks versus summer minima of each year.

The largest difference between peak and lull on any day of a year has increased from 22,585 MW in 2002 to 27,169 MW in 2009. Fig. 7.7 shows in particular how the daily differences between maxima and minima – the largest of which occur in winter – seem to be increasing year on year. This is not all, however. The smallest difference between peak and lull on any day of a year, has also increased from 7364 MW to 8415 MW, indicative that summer diurnal patterns in usage too are swinging from peak to lull by a greater amount.

Interestingly, the minimum difference between peak and lull on a day in any year between 2005 and 2009 is the same: 8415 MW. If daily oscillation patterns in electricity usage continue to grow larger then this could have a negative effect on the operational efficiency of generators and the wear and tear they incur as they vary their output to a greater extent to keep up with fluctuations in demand. Either way, proposals for ways to introduce demand levelling could be useful.

7.3.3 WEEKLY PATTERN

Electricity demand is clearly influenced by the "working week". In the UK and much of the West, the nine-to-five, five-day week is still seen as the typical way to earn a living [231]. Weeks are seven days long and starting from Monday there are 5 days of work – 'workdays' – followed by 2 days (often called 'weekends') of reduced activity. Historically Sunday has been a 'day of rest' [232] and despite many changes over the years, trading hours are by law still more limited on Sundays than on other days [233].

These patterns are harder to spot when years are laid one over another because the number of days in a year – 365 in a normal year, 366 in a leap year – is not divisible by seven. This means the same date for two different years corresponds to different days of the week, and that each year does not begin on the same day of the week.

In fact a year will only start on the same day of the week every 5, 6, or 11 years, depending on where leap years fall. Years starting per day of the week will only have occurred in equal numbers over a period of 28 years – this is how long researchers may have to wait before electricity demand can be analysed using years that start (and so hopefully also holidays and time changeovers) on the same day of the week. Fig. 7.8 shows how this introduces a lag effect when comparing two years that are seven years apart.

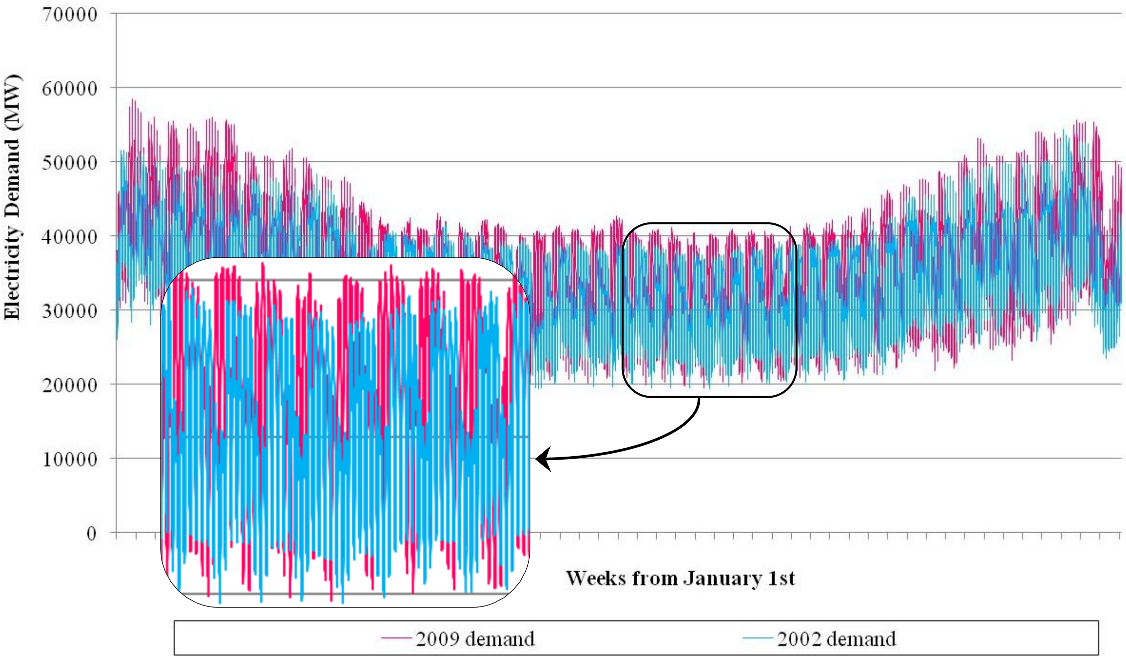


Fig. 7.8. Half-hourly annual data for the years 2002 and 2009 acquired from National Grid [8] laid over one another, indicating how use of the Gregorian calendar to determine start and end points for years, in combination with the seven-day working week, leads to lag effect when comparing demand data between different years.

Excluding the occurrence of public holidays, electricity demand is markedly higher on workdays than on weekends and this pattern persists in every year of the dataset. Crucially the pattern holds when considering annual peaks in demand. If weeks of highest annual demand – the seven day period of time starting at 00:00 h on a Monday within which highest annual demand occurred for each year – are overlaid as they have been in Fig. 7.9, it can be seen that the highest annual peak demand invariably occurs on a workday. The highest annual demand has occurred four times on a Tuesday, three times on a Thursday, twice on a Monday, once on a Wednesday and never on a Friday, Saturday or Sunday from 2002 to 2011.

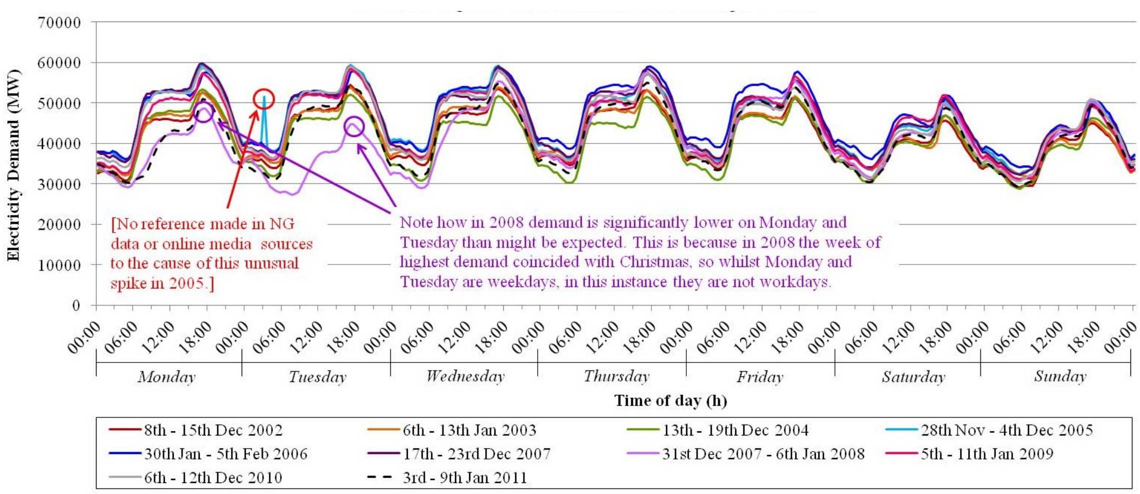


Fig. 7.9. National demand data for the weeks (beginning on a Monday at 00:00 h) that feature the highest annual demand for the years 2002 to 2009. Influence of the working week is clearly visible, as is the influence of the public holiday: Christmas. Data shown is half-hourly annual demand data acquired from National Grid [8].

Daily maxima appear to be influenced more strongly by the working week too. This can be seen in Fig. 7.10 which compares daily maxima against daily minima for the year 2009. Both daily maxima and minima are lower during weekends than during workdays, but maxima are more strongly affected by the working week than minima. The knock-on effect of this is that the difference between maxima and minima expands and contracts over the course of a week, the difference being at its largest on workdays and at its smallest on weekends.

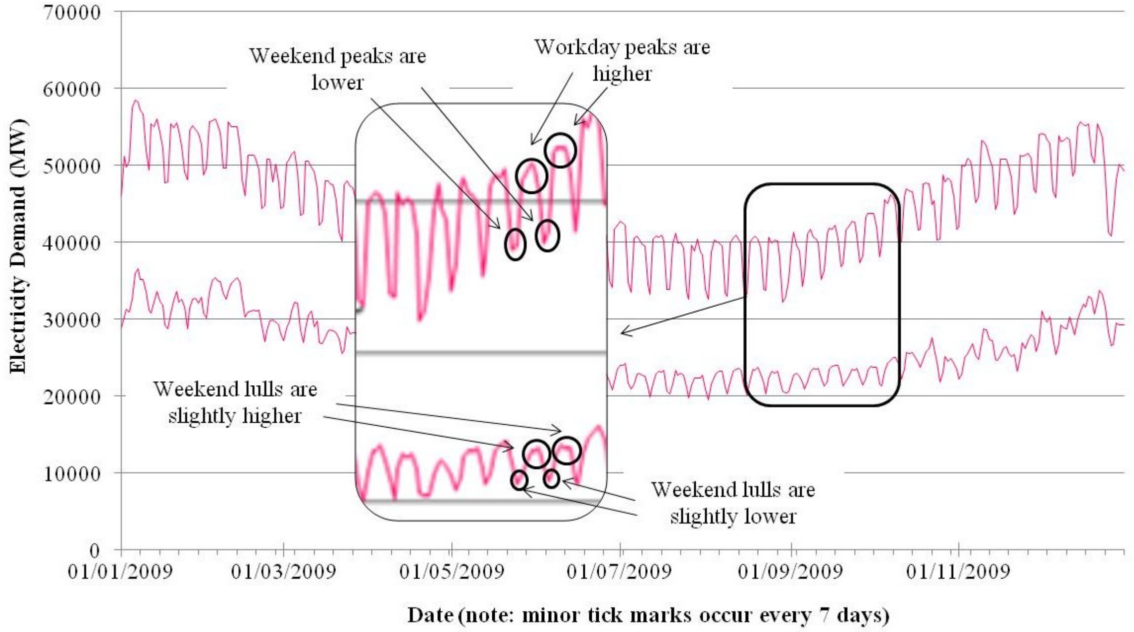


Fig. 7.10. Daily maxima (top) and minima (bottom) in national electricity demand plotted over the year 2009, calculated using half-hourly annual data from National Grid [8]. Both daily maxima and daily minima are affected by the working week and by seasons, but daily maxima vary by the greatest amount.

Fig. 7.11 plots the difference between daily maxima and minima over the same example year and shows how workday demand oscillates by a greater degree than weekend demand. The majority of the difference between workday and weekend demand can be attributed to changes in the magnitude of daily maxima as opposed to changes in daily minima, as evidenced when Fig. 7.10 and Fig. 7.11 are considered together.

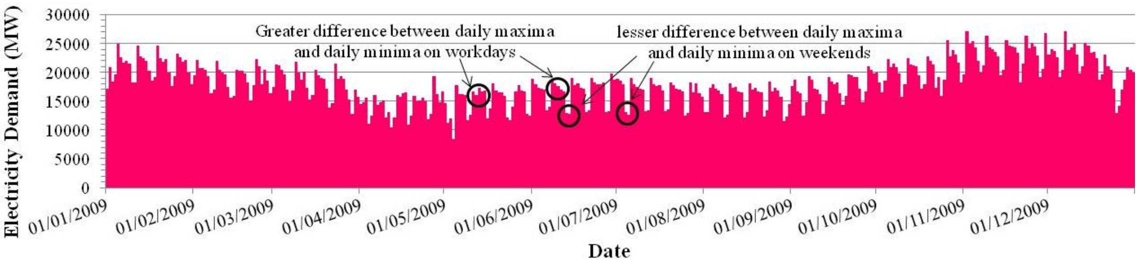


Fig. 7.11. Difference between daily maxima and minima over the course of the year 2009, calculated using half-hourly annual data from National Grid [8]. Workday demand oscillates by a greater degree than weekend demand.

7.3.4 PUBLIC HOLIDAYS AND TIME CHANGEOVERS

The impact of nationally adopted holiday periods on electricity demand is substantial. The Christmas and New Year's period in particular shows a stark, temporary reduction in electricity usage, breaking the seasonal winter peak in half (see Fig. 7.2, Fig. 7.3 and Fig 7.6). Other holidays can be identified as lull periods too, most notably Easter as it involves a bank holiday either side of a weekend (see Fig. 7.12).

Time changeovers – from British Summer Time (BST) to British Winter Time (BWT) or vice-versa – also contribute to distortions in electricity demand weekly patterns. BST to BWT shows less distortion (in Fig. 7.12 it is barely noticeable) but changeovers from BWT to BST where an hour is lost seems to have a lasting distortion effect for up to a week afterwards[18].

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[18] It seems losing an hour is more difficult for people to adjust to than gaining an hour!

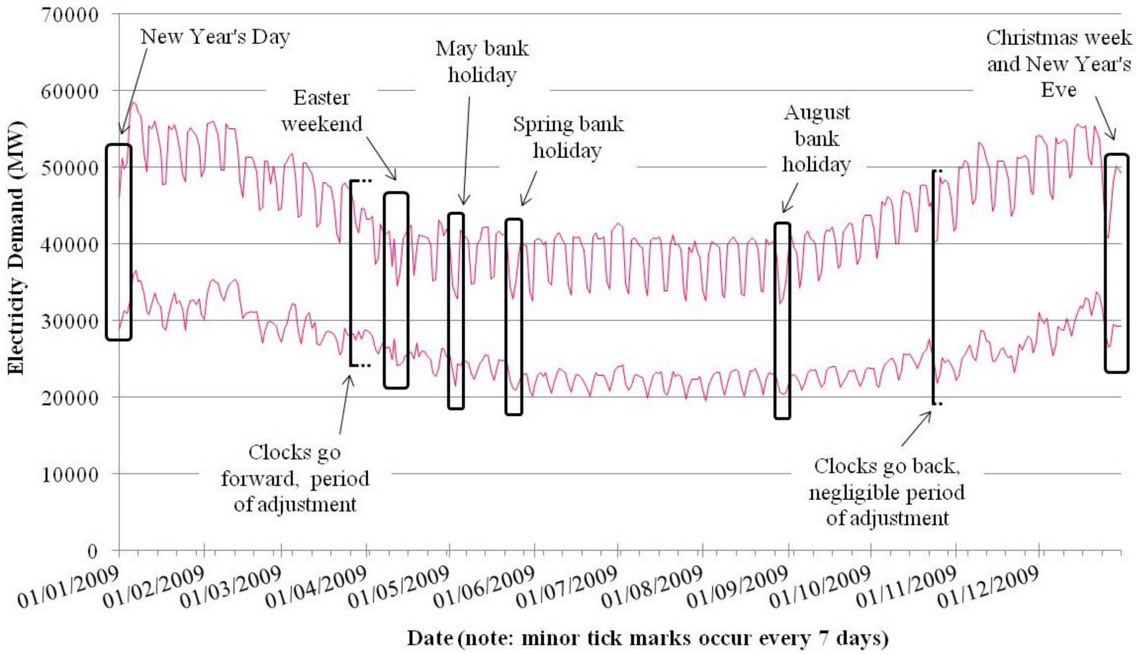


Fig. 7.12. The influence of national holiday and time change-over periods on daily maxima and daily minima in demand over the year 2009. Daily maxima and minima calculated using half-hourly annual demand data acquired from National Grid [8].

7.4 SUMMARY AND DISCUSSION OF FINDINGS

The highest recorded magnitude of electricity demand for Great Britain met by the electricity supply network over the period from 2002 to 2009 was 59,980 MW. Recurring patterns for lulls and peaks have also been identified:

- Peaks occur every evening, working day demand is always higher than that on weekends and winter introduces a seasonal peak for every year.
- Lulls in existing electricity demand occur nightly, on weekends and during summer months.

Should the burden of recharging loads prove too large for the national supply system, considering scheduling plug-in vehicle demand to coincide with these well-established patterns in the timing of lulls may help.

Seasonal lulls are unlikely to be taken advantage of by plug-in vehicles because of the timeframes involved. The average mileage travelled by identified PHEV eligible vehicles established in Chapter 6 ranged between 60.1 and 76.7 miles, but the AER given for PHEV eligible vehicles surveyed in the Chapter 5 ranged between 14.3 and 50 miles. The average mileage travelled by identified BEV eligible vehicles in Chapter 6 ranged between 20.7 and 22.9 miles, while their maximum mileage range is between 93 and 115 miles.

From these figures it can be assumed an average BEV eligible is vehicle likely to deplete its entire store of electrical energy within a week or even a few days. In the case of PHEV eligible vehicles, batteries are likely to be depleted in less than one day. It is therefore impractical to assume drivers of either type of vehicle could wait the several months before the next seasonal lull begins before recharging their vehicle's batteries.

On the other hand, daily and weekly patterns in the timing, duration and magnitude of existing loads could offer opportunities for recharging scheduling. In particular recharging scheduling should focus upon avoiding coincidence with existing daily peaks which have invariably occurred around 17:00 – 17:30 h (and always on a workday) and upon taking advantage of early-morning lulls and possibly also weekend lulls.

Of the years surveyed – 2002 to 2011 – the highest annual demand recorded was that for Monday 17th December 2007, where demand reached 59,880 MW. Later years however recorded lower peak demands. At the time the decision was made about which year/which week to use to test plug-in vehicle recharging, 2009 was the most recent year with available demand data. With a bad recession looming, 2009 was chosen as a compromise between basing the study on the year of highest known demand and basing it on the most recent year, with a lesser demand as might follow worsening economic depression, but one that could have been followed by years of higher demand if the economic depression proved fleeting.

It was not known how hard the recession would strike, nor if it would support or undermine the growing interest manufacturers had in selling plug-in vehicles. Rising oil prices for example might make plug-in vehicles more appealing, but if potential buyers had less disposable cash would this make purchase of plug-in vehicles less likely? 2009 might also have been the last year of data that gave a good picture of existing patterns in national demand, without the added influence of plug-in vehicles. Several plug-in vehicles were expected to debut from 2010 onwards.

The highest peak demand recorded from the years 2002 to 2009 (noted earlier as 59,880 MW) was rounded up to the nearest 1000 MW to give an arbitrary limit of 60,000 MW for testing impacts. That limit and the demand data for the year 2009 will next be used to construct scenarios to test the impact of plug-in vehicle recharging and to structure scheduling of plug-in vehicle loads in the next chapter.

CHAPTER 8: MAKING SCENARIOS

Previous chapters have gathered information as part of the Parry Tool outlined in Chapter 1. Chapters 2 through 4 provided the justification for proposing that road transport be shifted away from petroleum products dependency and towards electricity dependency (preliminary work, answering secondary research questions). Chapters 5 through 7 represented the main work and primary research interests. In this chapter, the applications of the Parry Tool are exampled to:

- Construct recharging loads that are added to existing demand over the chosen test week (Chapter 7) to investigate the impact of unrestricted recharging
- Inform the design of Recharging Regimes and workday-to-weekend load-shifting to complement identified patterns in existing demand (Chapter 7), then add the modified recharging loads to existing demand over the chosen test week to investigate the impact of restricted recharging

This chapter as a whole therefore covers the design of three scenarios that use the information gathered so far to test what might happen if vehicles with recharging and range specifications outlined in Chapter 5, number as many and adopt usage patterns determined in Chapter 6, have their recharging loads added to the existing demand test week specified in Chapter 7, under the following alternative conditions:

1) No restrictions upon recharging
2) Recharging restricted to avoid peaks and level demand according to diurnal patterns in existing demand established in Chapter 7
3) Recharging restricted to avoid peaks and level demand according to diurnal patterns in existing demand, and to level demand according to working week patterns in existing demand, established in Chapter 7

A broad overview of the construction of these scenarios is provided in this chapter, with details including screenshots of the design processes for scenarios 2 and 3, provided in Appendix 3. Under scenario 2, a brief description of the design of the Recharging Regimes used for that scenario is included. Under scenario 3, a brief description of the design of the load-shifting technique used in that scenario is included.

Justification for the use of a time-block approach for the construction of Recharging Regimes is provided. Comparison of the scenario designs is given at the end of the chapter to summarise their differences and purposes prior to the end of chapter summary. All work in this chapter was carried out using MS Office Excel 2007.

8.1 SCENARIO 1 – UNRESTRICTED RECHARGING

In this part of Chapter 8 ownership estimates for BEV and PHEV eligible vehicles gathered from the NTS [1] by the NTS statistics extraction method in Chapter 6, are combined with vehicle specifications gathered from manufacturers as per Chapter 5, to produce recharging loads for BEV and PHEV populations using travel behaviour patterns established by the NTS statistics extraction method in Chapter 6, that are then applied to the test week chosen in Chapter 7. This constitutes scenario 1. Results, analysis and discussion will be presented in Chapter 9.

As summarised by Fig.8.1, scenario 1 has two variations: 1A does not consider any form of mileage variability amongst vehicle populations, but 1B introduces limited mileage variation according to travel behaviour identified by the NTS statistics extraction method in Chapter 6. Results and analysis will then be presented in the next chapter. Key points are highlighted here, but full details about the construction of scenarios 1A and 1B can be found in Appendix 3.

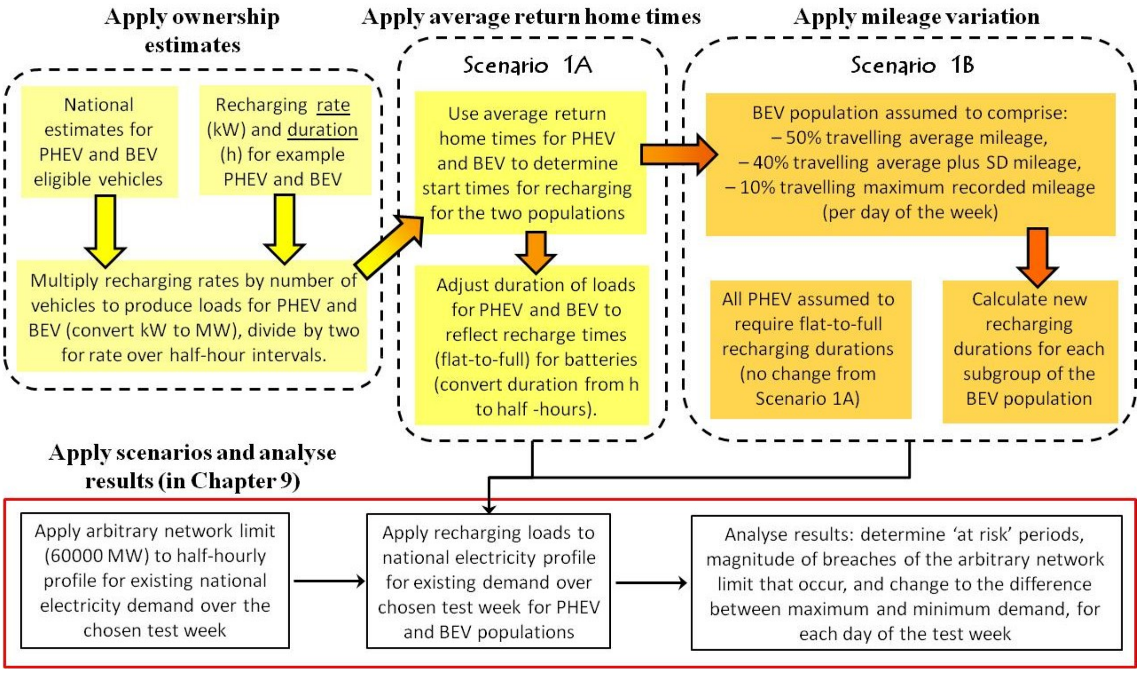


Fig. 8.1. Construction of scenario 1. Recharging rates and durations are as per specifications for the chosen example BEV and PHEV outlined in Chapter 5 of this study. Ownership estimates, average return home times, along with average mileage, SD for average mileage, and maximum mileage travelled, are all as determined by the NTS statistics extraction method in Chapter 6.

8.1.1 SCENARIO 1A

Average last return to home times listed in Chapter 6 under Table 6-3 were rounded up or down to the nearest half hour in order to be applied to the half-hourly national demand data from National Grid [8] of the chosen test week in Chapter 7. Despite the SD for first departure and last return to home times being large (typically ranging between 3 to 4 hours according to the analysis of NTS [1] in Chapter 6), only mean averages have been used. This was done to entertain the possibility of synchronised driving and recharging behaviour and to better illustrate the consequences of such a situation occurring.

Recharging rates for vehicles were assumed to be unaffected by battery SOC and therefore constant over the duration of recharging. For example, recovery from 10% to 30% SOC would occur at the same rate and therefore require the same duration of recharging as a recovery from 80% to 100% SOC.

8.1.1.1 A note on the use of half-hourly national demand data

The electricity demand profiles being used here are national and therefore do not reflect the true granular nature of demand at local levels, across different locations of the electricity distribution network. Demand data is limited to half-hourly intervals only, so impact assessment is further limited by the fact that fluctuations in demand occur over shorter time periods and battery recharging behaviour in reality may not be as linear as assumed here.

Impact assessment is further limited because despite the fact that the NTS [1] offers investigation of travel behaviour at a higher resolution, figures for departure and return times had to be rounded to the half hour to complement the half-hourly national electricity demand data used. Lastly an assumption is made to set an arbitrary network limit at 60,000 MW, but in reality there is a potential expectation for shortfall in supply due to closures of aging power stations coupled to a lack of new power stations coming online to take their place [234].

8.1.2 SCENARIO 1B (MILEAGE VARIATION APPLIED)

Scenario 1B is identical to 1A except that limited mileage variation has been applied. PHEV load durations are assumed unchanged in all scenarios. This is in fact a constant assumed across all scenarios, because it was found by the NTS statistics extraction method that mean average distances travelled for PHEV eligible vehicles exceeded the All Electric Range (AER) of the chosen example PHEV (see Fig.8.2). It was therefore assumed that PHEV would require their batteries to be recharged from flat-to-full, on every day of the test week in all three scenarios tested in this study.

Mileage variation was, however, applied to the BEV population in 1B. In accordance with the findings from the NTS statistics extraction method in Chapter 7, it was assumed that: 50% of the BEV population travelled average daily mileages, 40% travelled the average plus the SD for each day, whilst 10% of the population travelled the maximum mileage recorded for each day of the week. Again mileage was assumed to proxy energy usage and SOC depletion in a linear fashion.

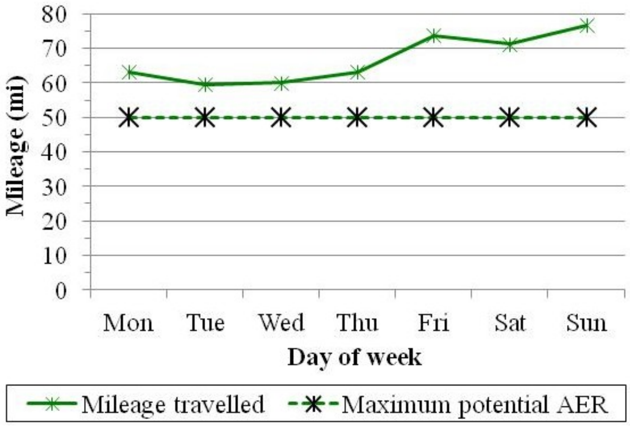


Fig. 8.2. Plotting average daily mileages for PHEV eligible vehicles against the maximum potential AER of the PHEV.

Recharging duration was assumed to be directly proportional to the amount of SOC required to be recovered. So recharging a battery from 60% to full (40% SOC difference) was assumed to take twice as long as recharging a battery from 80% to full (20% SOC difference). Recharging rate was again assumed to be unaffected by SOC. Recharging durations were rounded up or down to the nearest half-hour to again match the half-hourly demand data of the test week acquired from National Grid [8]. A breakdown of the BEV population showing mileage, subsequently calculated energy usage in kWh, and recharging duration for each day of the week is provided in Table A3-2 to Table A3-4 in Appendix 3.

8.2 SCENARIO 2 – RESTRICTED RECHARGING (RECHARGING REGIMES)

The preferred purpose of the Parry Tool is to inform the design of a suitable recharging load mitigation technique. Exampled here is the design of time-block based Recharging Regimes founded on the information gathered as part of the Parry Tool, by which total load is levelled whilst breach of the arbitrary network limit is avoided.

Justification for the use of a time-block technique will be explained separately prior to the summary at the end of this chapter. This part of the chapter instead provides a summary of Scenario 2 and the design and construction of Recharging Regimes.

Fig.8.3 summarises the construction of the two variations of scenario 2, with 2B being identical to 2A but for the addition of limited mileage variation for the BEV population in parallel with scenario 1B. Key points are given here, but full details can be found in Appendix 3. As shown in Fig.8.3, the construction of scenario 2 required the design of time-block groupings for plug-in vehicles to recharge at different times. A Recharging Regime strategy had to be determined in order to inform the division of BEV and PHEV into groups scheduled to start recharging at different times, then recharging groups had to be determined, with mileage variation applied for 2B.

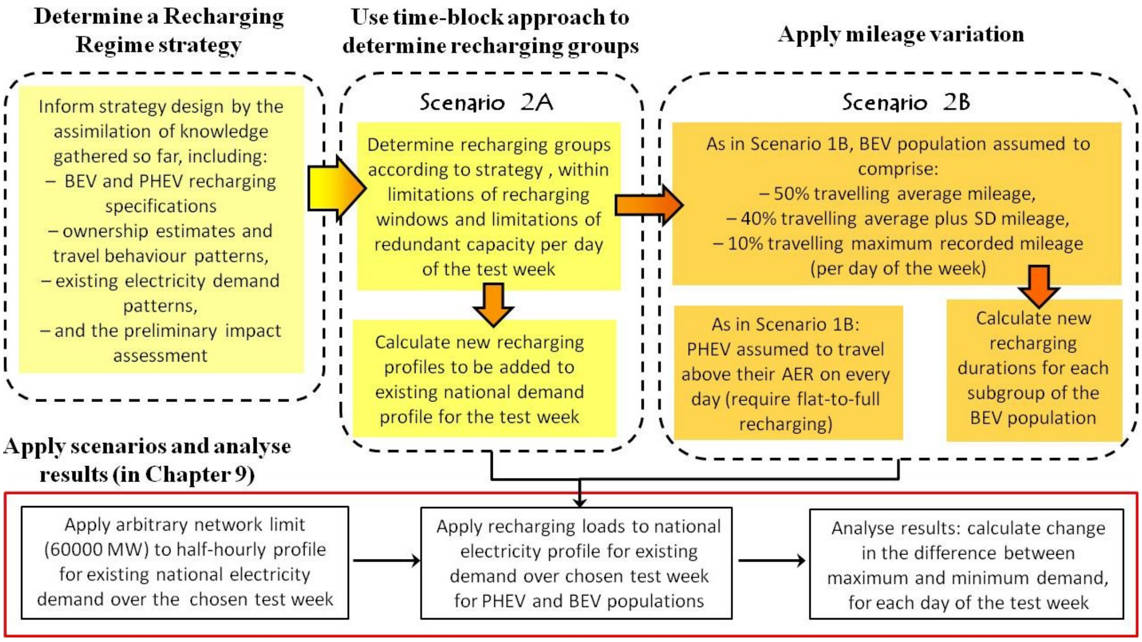


Fig. 8.3. Construction of scenario 2. Ownership estimates and recharging rates are as per scenario 1. Recharging durations are identical between 1A and 2A, and between 1B and 2B, reflecting assumptions about daily mileages travelled parallel between 1A and 2A, and between 1B and 2B.

8.2.1 RECHARGING REGIME DESIGN STRATEGY

The factors and questions used to inform the Recharging Regime design strategy are summarised in Fig. 8.4. The BEV population was deemed to be the larger threat, because their population size relative to that of the PHEV population more than compensates for their lower recharging rate, making them the larger load in need of spreading.

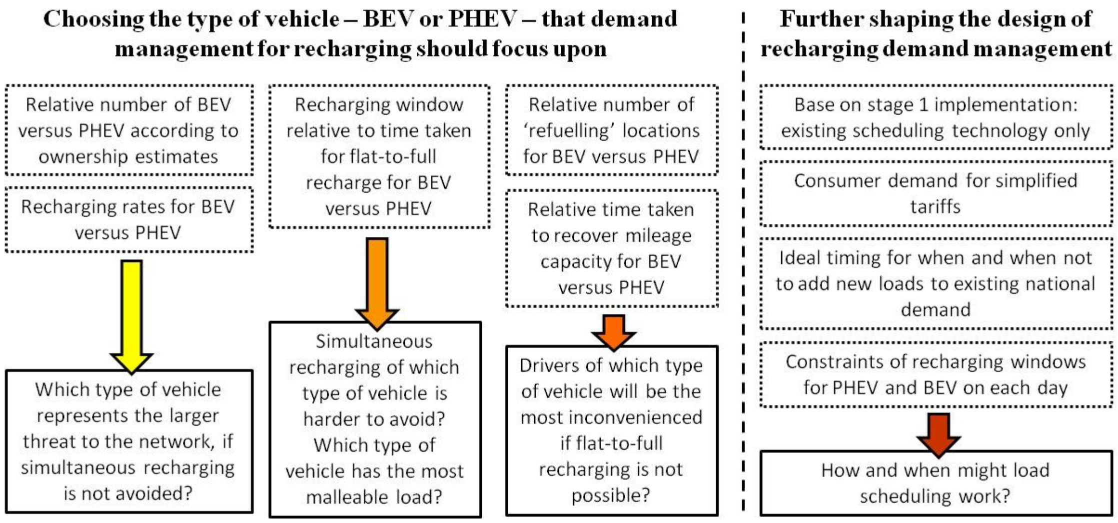


Fig. 8.4. Determining a Recharging Regime strategy to inform the division of BEV and PHEV into groups that start recharging at different times.

Unfortunately simultaneous recharging of BEV is unavoidable because of the size of their recharging window relative to the duration required for them to recharge from flat-to-full. Compounding the issue, it is drivers of BEV who will be the most inconvenienced if recharging falls short of that required to fully recover the energy stored in their vehicle's batteries because unlike PHEV, this is their sole storage form of energy and their mileage ranges are shorter.

Most of the vehicles reviewed in Chapter 5 had some facility for a timer to be set, and those that lacked this technology were said to be planning to include it in future models. Many also had the facility to plan an entire week's schedule for recharging so a week-long program was deemed feasible. The word 'regime' is used because even for the same recharging group, scheduled start times may differ day to day over that week.

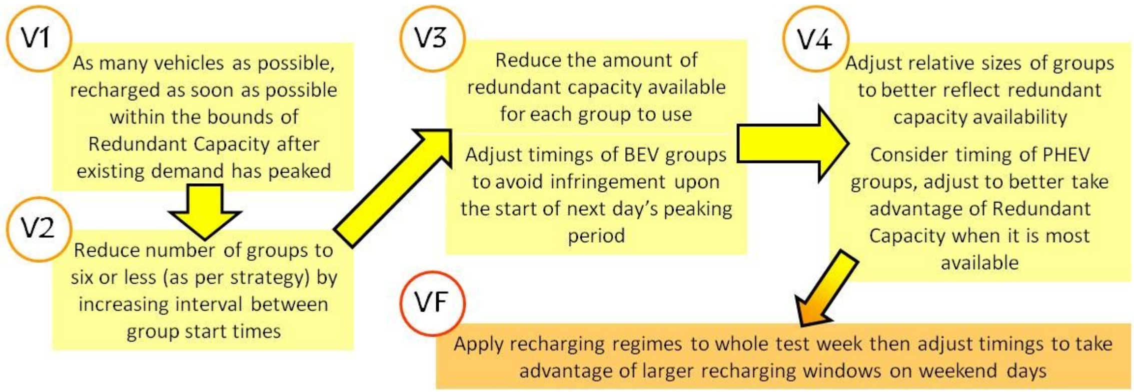
Energy consumers have called for simplified energy tariffs from energy suppliers [235], so if vehicle owners were to have a choice of such regimes offered to them by their energy supplier, it was assumed that less choice would be preferable. It was decided that recharging groups would therefore be limited to a maximum of six per type of vehicle.

Analysis of existing electricity demand in Chapter 7 highlighted the particular importance of diurnal and seasonal peaks but showed that the diurnal peak, when it coincides with the seasonal peak in a year to produce the annual maximum, is quite predictable: 17:00 h on every day of highest national electricity demand in every year between 2002 and 2009 recorded by National Grid [8]. There was only one exception where it was half an hour later (17:30 h), and every one of these occasions took place on a workday, not a weekend day. So it was decided that no recharging group should be scheduled to start recharging any earlier than 18:00 h and that the day of highest annual demand (included within the chosen test week), would be used as the standard by which to set the sizes and timings of those groups.

Start times and end times for recharging must also fit within the recharging windows established in Chapter 6 for each type of vehicle, BEV and PHEV. Times for first departures were rounded down to the nearest half hour, to indicate the last half-hour time slot that vehicles might be expected to be found recharging. It was also decided that the scheduling of recharging and splitting of vehicles into groups should be based on the accommodation of the worst case scenario and therefore that all vehicle require the longest possible recharging durations: to recharge their batteries from flat-to-full.

8.2.2 DETERMINING RECHARGING GROUPS AND TIMINGS

The design of Recharging Regimes then progressed through four versions before finalisation, as summarised in Fig.8.5. Initially this started with the simple calculation where Redundant Capacity – which is the difference between the arbitrary network limit of 60,000 MW and existing demand – was divided by the recharging rate of BEV (1.2 kW over half an hour) to work out how many BEV could begin recharging at each half-hour from 18:00 h. This was an iterative process that involved subtracting the Redundant Capacity in use by each preceding BEV group to calculate the number of BEV that could begin recharging at the next half-hourly slot. The step by step explanation of progression from version to version is provided in full in Appendix 3.



As many vehicles as possible, recharged as soon as possible within the bounds of Redundant Capacity after existing demand has peaked

Reduce number of groups to six or less (as per strategy) by increasing interval between group start times

Reduce the amount of redundant capacity available for each group to use

Adjust timings of BEV groups to avoid infringement upon the start of next day's peaking period

Adjust relative sizes of groups to better reflect redundant capacity availability

Consider timing of PHEV groups, adjust to better take advantage of Redundant Capacity when it is most available

Apply recharging regimes to whole test week then adjust timings to take advantage of larger recharging windows on weekend days

Fig. 8.5. Progression of Recharging Regime design, based on the day of highest annual electricity demand in 2009, through four versions. The final version (VF) took the group sizes and timings designed for that one day and applied them to the rest of the test week (week of highest demand in2009), making adjustments for weekend days to reflect larger recharging windows open to vehicles.

Version 1 (V1) determined the size and number of vehicles whose recharging needs could be met by Redundant Capacity if as many started recharging as possible, as early as possible. The groups were therefore scheduled only half an hour apart. V1 led to a very uneven distribution of BEV. which led to recharging loads rising sharply then declining sharply and resulted in the BEV having to be split into more than six groups.

In V2, the number of groups was reduced by spreading recharging start times (and the calculation of each time slot's group size), to start one hour apart, as opposed to only half an hour apart. PHEV were split into two groups and added when Redundant Capacity was sufficient to accommodate them.

In V3, the situation was further improved by allowing for a small amount of spare Redundant Capacity. This was done by iteratively halving the amount of Redundant Capacity that each recharging slot was allowed to use. So at 18:00 Redundant Capacity was halved and the number of BEV that could begin recharging at that time calculated as before. The next group was assumed to begin recharging at 19:00 h (following on from changes made in V2). Having first subtracted the amount of Redundant Capacity assumed to be taken by the recharging of the first group which began at 18:00 and would still be recharging, the remaining Redundant Capacity was halved and the number of vehicles that could begin recharging in the second group at 19:00 h was calculated. This process was repeated until all BEV were allocated a group, with the number of groups for BEV increasing from four to six.

An unintended consequence of having spread recharging start times and allowed for spare Redundant Capacity, was that the BEV recharging load began to impinge on the start of the next day's peaking period. End time for recharging of the last group was at 09:30 h, meaning that group completed recharging half an hour after the recharging window on that day for BEV had closed. To solve this, the timings of the last two recharging groups were adjusted so that they would finish recharging earlier.

In V4, BEV group sizes were manually adjusted slightly to better reflect the availability of Redundant Capacity. Lastly the timing of the PHEV recharging groups was considered more closely and adjusted toward the same goal.

In the final version (VF), having established recharging group sizes and timings for BEV and PHEV based on the day of highest existing demand, the recharging schedule from version 4 was applied to every day of the test week. Acknowledging that recharging windows are larger over weekend days, group timings were adjusted to allow wider spreading of recharging loads on Friday and Saturday. Sunday's recharging schedule remained unchanged however, as the widening of the recharging window (starting at an earlier time) offered no advantage on that day because of the timing of the existing demand peak.

Finalised recharging groups sizes are listed in Appendix 3 under Table A3-8 for BEV and A3-9 for PHEV. Start times for recharging are listed in Appendix 3 under Table A3-10 for BEV and A3-11 for PHEV. These Recharging Regimes form the basis for testing the impacts of recharging demand in scenario 2. Graphs comparing recharging load features between this scenario and others can be found in the Scenarios Comparison part of this chapter.

8.2.3 APPLYING MILEAGE VARIATION (2B)

The difference between 2A and 2B is that in 2B, mileage variation is applied (as it was in 1B). So 50% of the BEV population are assumed to be travelling average daily mileages, 40% are assumed to be travelling average plus SD mileages each day, and 10% as assumed to be travelling the maximum recorded mileage on each day. This is applied by assuming each recharging group proportionally reflects this travel behaviour breakdown of the total BEV population. Each recharging group therefore has the same 50-40-10 breakdown of mileage variation, which in turn affects the duration of recharging assumed for those vehicles. The same tables for calculating load durations were used in 2B as in 1B (see Appendix 3). Graphs comparing recharging load features between this scenario and others can be found in the Scenarios Comparison part of this chapter.

8.3 SCENARIO 3 – WORKDAY TO WEEKEND LOAD-SHIFTING

Fig 8.6 summarises the construction of the two variations of scenario 3, with both being identical to 2B (including application of limited mileage variation) but for the partial decoupling of mileage travelled from recharging duration received by BEV. This decoupling is the result of allowing, in scenario 3, the partial recharging of vehicle batteries so as to permit the shifting of loads from workdays to weekends.

Both 3A and 3B are therefore comparable to 1B (unrestricted recharging with the application of limited mileage variation for BEV) and 2B (recharging restricted by Recharging Regimes, with the application of limited mileage variation for BEV). Design basics are covered first, followed by a brief description for how basic load-shifting was applied in 3A (including emergency mileage allowance). Lastly a brief description is given for improvements made upon load-shifting in 3B to balance loads occurring on workdays more evenly over workdays, and to balance loads occurring on weekend days more evenly over the weekend. Further details can be found in Appendix 3.

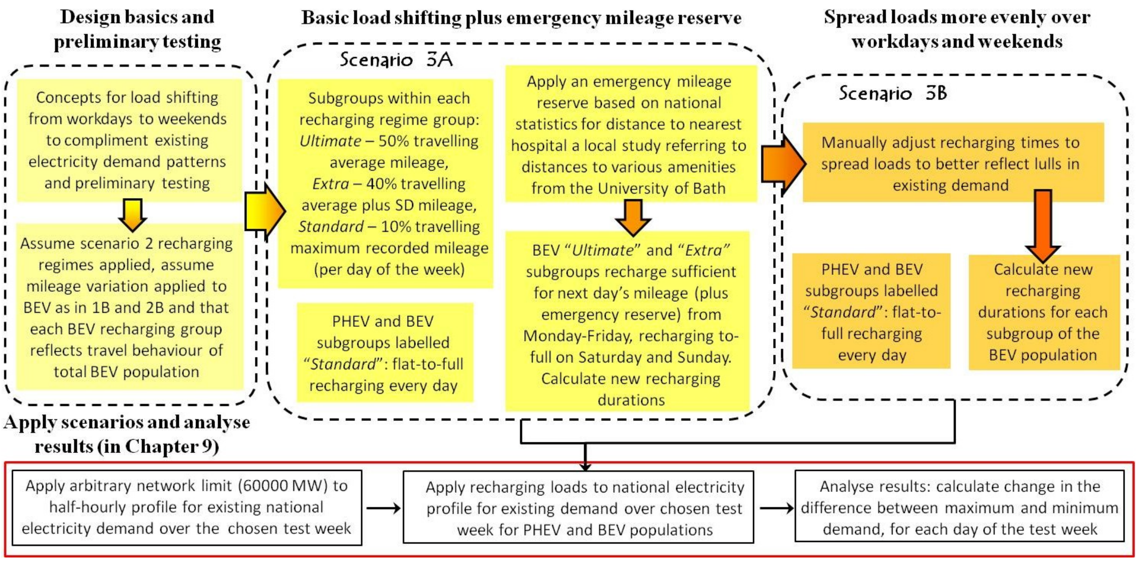


Fig. 8.6. Construction of scenario 3. Ownership estimates and recharging rates are as per scenarios 1 and 2. Assumed daily mileages are identical to those assumed for 1B and 2B only, but recharging durations have been partly decoupled from mileage in order to allow for partial recharging and subsequent load-shifting between days of the week, specifically for BEV travelling average or average plus SD mileages.

8.3.1 LOAD-SHIFTING DESIGN BASICS

Drawing upon patterns in existing national electricity demand highlighted in Chapter 7, it was envisioned that recharging loads might be shifted from workdays to weekends. The plan for this being that plug-in vehicles may be able to take advantage of the weekly pattern seen in existing demand, where there is greater availability of Redundant Capacity on weekends than on workdays.

In 1B, 2B and in both 3A and 3B as mentioned before, limited mileage variation across the BEV population is assumed. After the application of Recharging Regimes, it was assumed as in 2B that each BEV recharging group proportionally reflected the mileage variation assumed for the whole BEV population. This meant that the BEV recharging groups could each be broken down into three subgroups by their mileage (calculations for load durations were already performed and used for 1B and 2B), then named[19] according to their suitability for load-shifting:

- '*Ultimate'* represented the 50% of vehicles travelling average daily mileages,
- '*Extra'* represented the 40% travelling average plus SD daily mileages
- '*Standard'* represented the 10% of vehicles travelling maximum daily mileages.

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[19] These names were envisioned to reflect the tariff add-ons that a supplier might offer an electricity consumer with a plug-in vehicle, after giving them the choice of the 6 Recharging Regime patterns for daily timing of recharting.

Vehicles in the *Standard* subgroups were assumed to have zero capacity for load-shifting. Vehicles in the *Ultimate* subgroup were assumed to have the most capacity for load-shifting, whilst *Extra* had some capacity but not as much as vehicles in *Ultimate* subgroups. Two concepts were envisioned:

1) Weekend-only recharging
2) Partial recharging on workdays then recharging to full on weekends

These are described visually in Fig. 8.7. Testing (see Appendix 3) subsequently proved that weekend-only recharging would be unsuitable, even for vehicles in the *Ultimate* category. So partial recharging was investigated as the premise for 'basic load-shifting' in 3A.

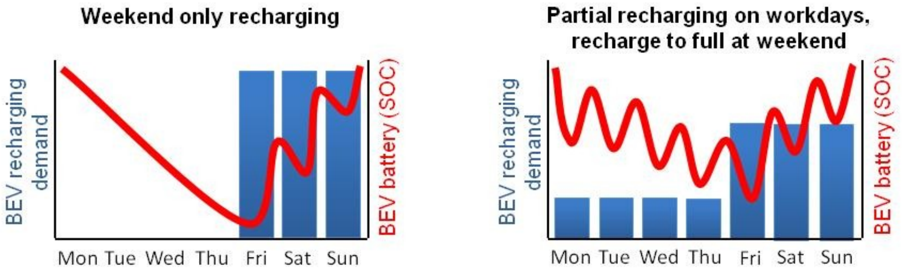


Fig. 8.7. Concept ideas for taking advantage of weekend lulls in electricity demand. In the first concept (left) recharging only occurs on weekends. In the second concept, partial recharging on workdays is used with 'to-full' recharging scheduled for weekends. Concept diagrams adapted from project work presented at the 45th Universities Power Engineering Conference [182].

8.3.2 BASIC LOAD-SHIFTING (3A)

In basic load-shifting, the BEV in *Ultimate* and *Extra* subgroups were recharged on workdays Monday to Friday but to only sufficiently recover the SOC equivalent to the number of miles expected to be covered the next day, plus an emergency mileage reserve. On Saturday and Sunday the vehicles were allowed to recover SOC to full. The number of miles driving a vehicle could perform was assumed to be directly proportional to battery SOC and again recharging rates were assumed unaffected by SOC so recharging duration was directly proportional to SOC to be recuperated. Full details for how these calculations were carried out are provided in Appendix 3.

As noted above, it was assumed that some allowance for an emergency mileage reserve should be made for drivers adopting partial recharging for load-shifting. Emergencies happen and unplanned events can affect a person's travel needs. It is therefore unwise to assume that recharging should allow for only the expected mileage for the next day. Nevertheless, assessing realistically how much mileage should be set aside for emergencies is not an easy task. A basic assessment is provided in this study, that considered two factors:

- Medical emergencies – be they for the driver, a passenger, or to visit a friend or family member and,
- Unplanned but non-emergency travel such as picking up children from school when the school is forced to close due to bad weather.

According to Maslow's priority of needs [118] a person will seek to meet their most basic needs first. So whilst covering expected mileages is important to drivers, reserving mileage in case a higher, unexpected priority presents itself such as the need to access medical care, will also be important to drivers.

In 2012, the Co-operation and Competition Panel for NHS-funded Services included the in their "Working Paper Series – Volume 1 Number 4: Choices of NHS funded hospitals in England" [236], an analysis of Hospital Episode Statistics (HES) data collected by the NHS Information Centre for Payment by Results. Fig. 8.8, adapted from Fig. 1 in the report, shows the average distance that patients would need to travel to reach their nearest hospital, assuming that particular hospital was the one they chose to or needed to go to for care.

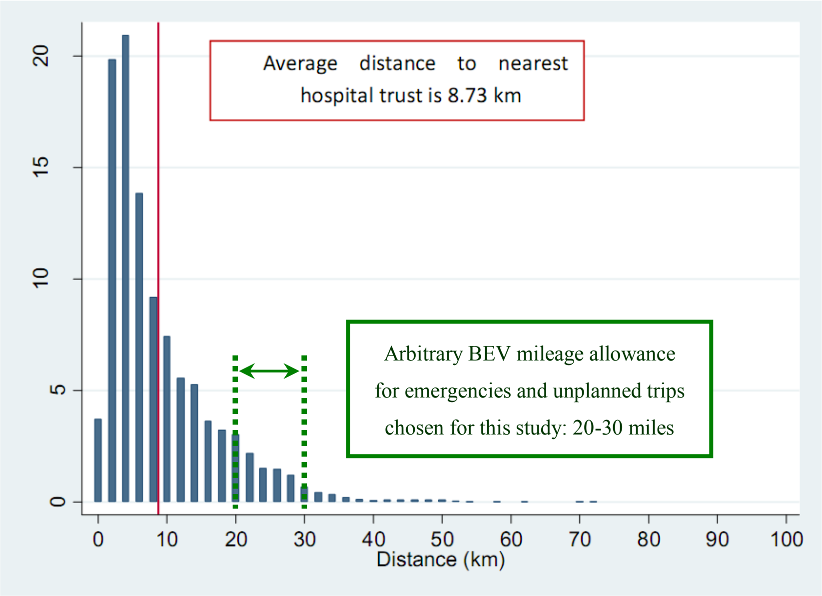


Fig. 8.8. Distances to hospitals from home for 51505 elective hip replacement patients – adapted from "Fig. 1: Distance to nearest hospital trust" from [236] which presented findings from an analysis of Hospital Episode Statistics (HES) data collected by the NHS Information Centre for Payment by Results.

The analysis was based on a sample of 51,505 elective hip replacement patients, 146 NHS and Foundation Trusts and 216 hospital sites. A reserve of 20-30 miles was assumed the minimum to allow for an emergency. As can be seen in Fig. 8.8, the vast majority of patients in the study's HES analysis would require far less than the arbitrary amount set for this project indicated in green, but this allowance seemed to be a reasonable compromise between accommodating for emergencies and unplanned trips whilst keeping required recharging on workdays as low as possible. This choice is supported by statistics reported for far smaller, local study, which considered distances to local amenities when setting aside SOC reserve for electric cars brought to the campus of the University of Bath by staff and students, before determining SOC available for V2G services:

> *"9 of the nearest hospitals to the university are within less than 20 miles of the University [of Bath], whilst many schools, shops, social places and driver residences are also within 10 miles from the campus..."*
>
> Pu *et al.*, from [237]

More details about the calculations involved in load-shifting and the allocation of an emergency mileage reserve can be found in Appendix 3, along with tables detailing the load duration modifications for the BEV recharging subgroups *Ultimate* and *Extra* to which they apply. Graphs comparing recharging load features between this scenario and others can be found in the Scenarios Comparison part of this chapter.

8.3.3 ADVANCED LOAD-SHIFTING (3B)

In 3B the recharging durations calculated for 3A were manually adjusted to balance loads more evenly, across workdays for workday loads, and across weekend days for weekend loads. MS Excel's conditional formatting tool was used to ensure that SOC upon completion of recharging always fell within the threshold required to match the inclusion of both next day's driving and the 20-30 mile emergency mileage reserve.

This process can be seen in more detail in the Appendix 3. Tables detailing the load duration modifications for the BEV recharging subgroups *Ultimate* and *Extra* will be provided in the results for comparison to 3A and 2B. Graphs showing the difference these modifications have made can be compared against the loads for vehicles in other scenarios in the Scenarios Comparison part of this chapter.

8.4 JUSTIFICATION FOR TIME-BLOCK APPROACH TO RECHARGING REGIMES

As has been noted previously, much research worldwide has gone into the vision and design of ways to use responsive plug-in vehicle recharging demands to adjust the impact of plug-in vehicle recharging on electricity supply networks [56, 138, 139, 150, 152, 157, 160-176]. A monitoring and control infrastructure and system, welcomed by consumers, in place by the time that plug-in vehicles are of a sufficient number to warrant its existence, is however a standard assumption made in all of these references barring a very few exceptions. Of the exceptions that included or assumed customer control of recharging, recharging was assumed to take place unrestricted (recharging upon returning home or at the end of a journey), or at a singular specified 'off-peak' time.

In contrast this study has focused on present day statistics and present day technology in order to give a better perspective on the intermediate period between now and the advent of such technology and its public adoption. There has been much negative press regarding the monitoring of people's daily lives and activities by third parties via cars [177], Smart Meters [178] and Facebook [179], which means consumer control of recharging will be the more likely adopted practice in the beginning.

Financing for the design, manufacture and implementation of a monitoring and control mechanism for recharging would have to be justified both by assured need on the part of the electricity supply system stakeholders, but also by interest on the part of the consumer. This would take time to develop. So without substantial forward planning, financial investment and a leap of faith to implement the system prior to need, a lag would likely develop between need for recharging control, and the implementation of suitable smart grid systems for monitoring and controlling recharging.

It is important therefore to have some means of handling the recharging of large numbers of plug-in vehicles that is based on consumer-controlled recharging to cover that intermediate period of time. It may perhaps also be wise to have such a scheme in place for emergencies, to cover any occasion where the monitoring and control system experience down-time, but the electricity supply system is still up and running. Bugs in the system, environmental disaster, or disruption due to malicious meddling, there are plenty of reasons why such an event might occur.

A worst-case scenario would paint the advent of plug-in vehicles and their recharging completely unregulated for several years... Until a threshold is reached that means it must be regulated for sake of all stakeholders, but that the customer stakeholder rejects the imposition of such a system based on habitual routine and privacy concerns, and/or the perceived meddling of authority figures in matters of personal liberty. Restricted recharging implemented by consumers, however, could lay the foundations for customer interest in a monitoring and control system, as a relief from what may have, by that point, become a tiresome routine of following instructions for implementing Recharging Regimes manually.

8.4.1 SIMULTANEOUS RECHARGING – PRELIMINARY THEORETICAL TESTING

As noted previously, the studies that were found (those which considered vehicle owner control of recharging) only considered unrestricted recharging, or recharging restricted to one ‘off-peak’ time slot. In particular, no effort was made to avoid simultaneity of recharging. Preliminary testing suggested this may be unwise if for any reason, third party monitoring and control of recharging does not come to fruition whilst numbers of PHEV and BEV increase to match the estimates for PHEV and BEV eligible vehicles in this study.

Fig 8.9 shows the theoretical testing of loads for simultaneous recharging of all BEV, of all PHEV and of all BEV and PHEV together, were those vehicles to be found recharging at any half hour over the test week. The arbitrary network limit of 60,000 MW is marked for reference.

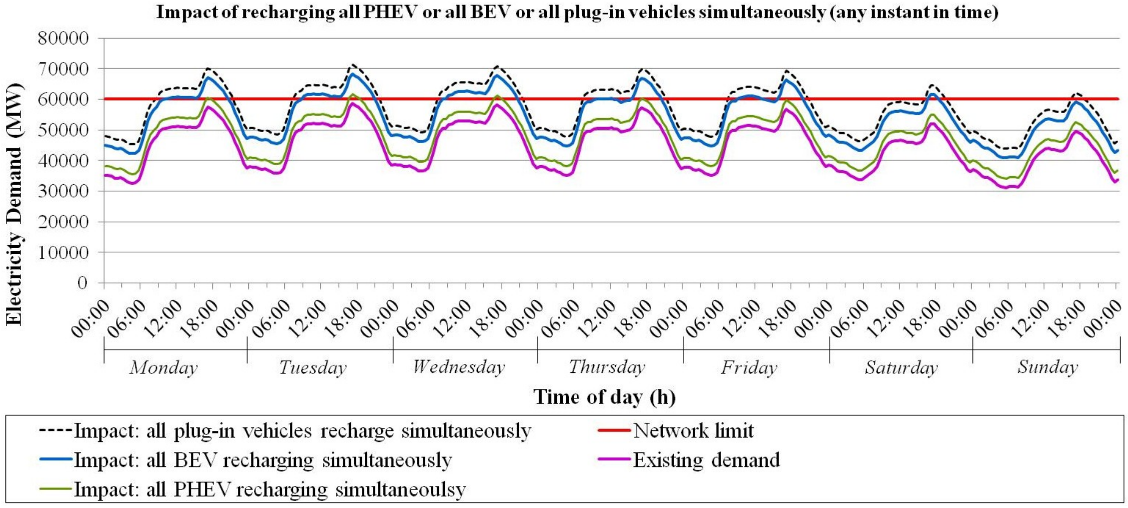


Fig. 8.9. Theoretical impact upon national electricity demand if all BEV, all PHEV and all plug-in vehicles (all BEV and all PHEV) to recharge simultaneously for every half hour for the duration of the test week.

Table 8-1 provides a breakdown analysis of ‘at risk periods’ where addition of simultaneous recharging loads for PHEV, BEV or all BEV and PHEV together would push total demand over the arbitrary network limit. If synchronised PHEV recharging is the sole recharging load present then the potential magnitude for breaching the network limit is relatively small – no greater than 1556.5 MW over each half-hour period. At-risk periods for simultaneous PHEV recharging are also relatively small – no greater than 2.0 h.

Table 8-1: Theoretical impact were all BEV, all PHEV, and all plug-in vehicles (all BEV and all PHEV together) to recharge simultaneously for every hour of the test week: new daily peaks, magnitudes by which those peaks breach the arbitrary network limit and length of at-risk periods where demand peaks above the arbitrary network limit on each day.

Day of the week	New peak (MW) when simultaneously recharging[1]			Magnitude of breach (MW) above 60000 MW limit			Duration of at-risk period[2] (h)		
	PHEV	BEV	All plug in vehicles	PHEV	BEV	All plug in vehicles	PHEV	BEV	All plug in vehicles
Mon	60477.5	67108.0	70110.5	477.5	7108	10110.5	0.5	10.5	13.0
Tue	61556.6	68187.0	71189.5	1556.5	8187.0	11189.5	2.0	12.0	14.0
Wed	61228.5	67859.0	70861.5	1228.5	7859.0	10861.5	1.5	12.5	14.0
Thu	60176.5	66807.0	69809.5	176.5	6807.0	9809.5	0.5	8.0	14.0
Fri	59862.5	66313.0	69315.5	0.0	6313.0	9315.5	0.0	8.5	13.5
Sat	54943.5	61574.0	65476.5	0.0	1574.0	4576.5	0.0	2.0	3.5
Sun	52432.5	59063.0	62065.5	0.0	0.0	2065.5	0.0	0.0	2.5
All days	**61556.5**	**68187.0**	**71189.5**	**1556.5**	**8187.0**	**11189.5**	**4.5**	**53.5**	**74.5**

[1] Pale red used to highlight where demand breaches arbitrary 60,000 MW limit.

[2] For BEV Thursday and Friday actually have two at-risk periods separated by a 1 h interval. On Thursday the first is 4.5 h long, the second 6 h long. For Friday the first is 5.5 h long, the second 4.5 h.

Simultaneous BEV recharging, however, could breach network limit on any day but Sunday. The potential magnitude for breaching the network limit is larger for BEV than for PHEV – up to 8187.0 MW. At-risk periods for simultaneous BEV recharging are also far larger – no less than 8.0 h on any workday with the longest at-risk period lasting 12.5 h.

The greatest recharging impact arises where simultaneous recharging of all plug-in vehicles is considered. Workdays, specifically Monday to Friday, have the worst potential magnitudes for network breaches ranging from 9315.5 to 11189.5 MW over a half-hour. Even on Sunday, the potential magnitude for breach is no less than 2065.5 MW. At risk periods are no smaller than 2.5 h on any day of the week of the test week and ay their worst are also larger, the largest being 14.0 h on each of Monday, Tuesday and Wednesday. Workday at-risk periods range between 13.0 and 14.0 h. Weekend at-risk periods are considerably smaller: 3.5 h long on Saturday, 2.5 h on Sunday.

Staggering recharging loads from vehicles would reduce the timeframes over which the network could be at risk. Staggering loads could also deal with another problem that simultaneity of recharging could cause: sharp spikes in demand as vehicles begin recharging at, or close to, the same time. Sharp spikes in demand are not conducive to the healthy and efficient operation of electricity generation and supply networks. Although not reflected in the loads built in these scenarios, there is also the ever-present variety of human travel behaviour to consider, meaning that one off-peak time may not suit all, because of the timing of recharging windows. So a time-slot allocation of groupings for vehicles was considered to manage their recharging demand in scenario 2 and scenario 3.

8.5 SCENARIOS COMPARISON

The scenarios in this study are constructed to enable, through comparison, a better understanding of how assumptions about daily mileages travelled, recharging scheduling and load-shifting can influence the magnitude, duration, timing and shape of the resultant total load when plug-in vehicle recharging loads are added to existing loads.

Results are presented in the next chapter, but an overview of the differences in these underlying factors is given here as a summary. Comparisons are made to show differences between assumed daily mileages, assumed post recharging battery SOC and recharging durations for different scenarios and for different variations within scenarios.

8.5.1 DIFFERENCES IN ASSUMED MILEAGES

Daily mileages for PHEV and BEV are unchanged when comparing 1A and 2A. They are also unchanged when comparing 1B, 2B, 3A and 3B. Fig. 8.10 and Fig. 8.11 compare the daily mileages assumed for plug-in vehicles over the test week for the three different scenarios and their variations.

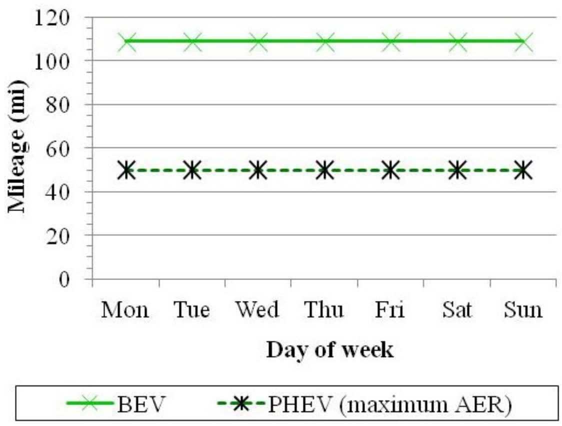


Fig. 8.10. In 1A and 2A, BEV were assumed to travel their maximum range. PHEV of their batteries (AER) is given here in miles for reference.

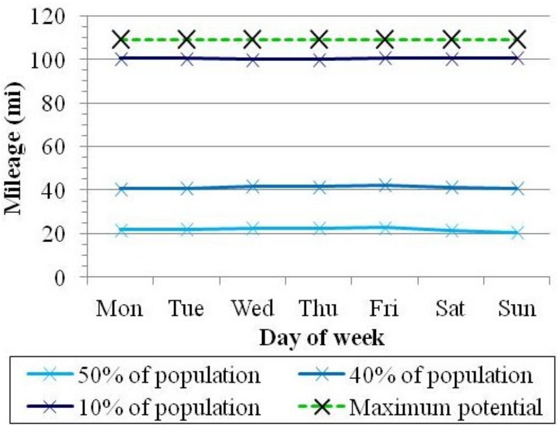


Fig. 8.11. Scenarios 1B, 2B, 3A and 3B assumed BEV were split into three groups in a 50:40:10 ratio travelling different daily mileages. The maximum potential range of BEV is given here only for reference.

Note that in Fig. 8.10 that the AER (all electric range) of PHEV is given as opposed to their actual daily mileages. This is because in this study, PHEV are assumed to be travelling mileages above their AER on every day under all scenario conditions (see previous Fig. 8.2), requiring a flat-to-full recharge every night. In 1A and 2A, 100% of BEV are assumed to require flat-to-full recharging, having utilised their maximum range on every day of the week. (see Fig. 8.10). In 1B, 2B, 3A and 3B (see Fig. 8.11), 50% of BEV are assumed to travel average daily mileages, 40% are assumed to travel the average mileage plus the SD mileage on each day. 10% are assumed to travel the maximum mileage.

8.5.2 DIFFERENCES IN SOC

Fig. 8.12 compares the post-recharging SOC for plug-in vehicles over the test week for the different scenarios and their variations. PHEV are assumed to be recharged to 100% SOC every night in every variation of every scenario. This assumption is assumed also for BEV in scenarios 1 and 2 (both A and B variations of each), meaning that SOC after recharging is identical for scenarios 1A, 1B, 2A and 2B.

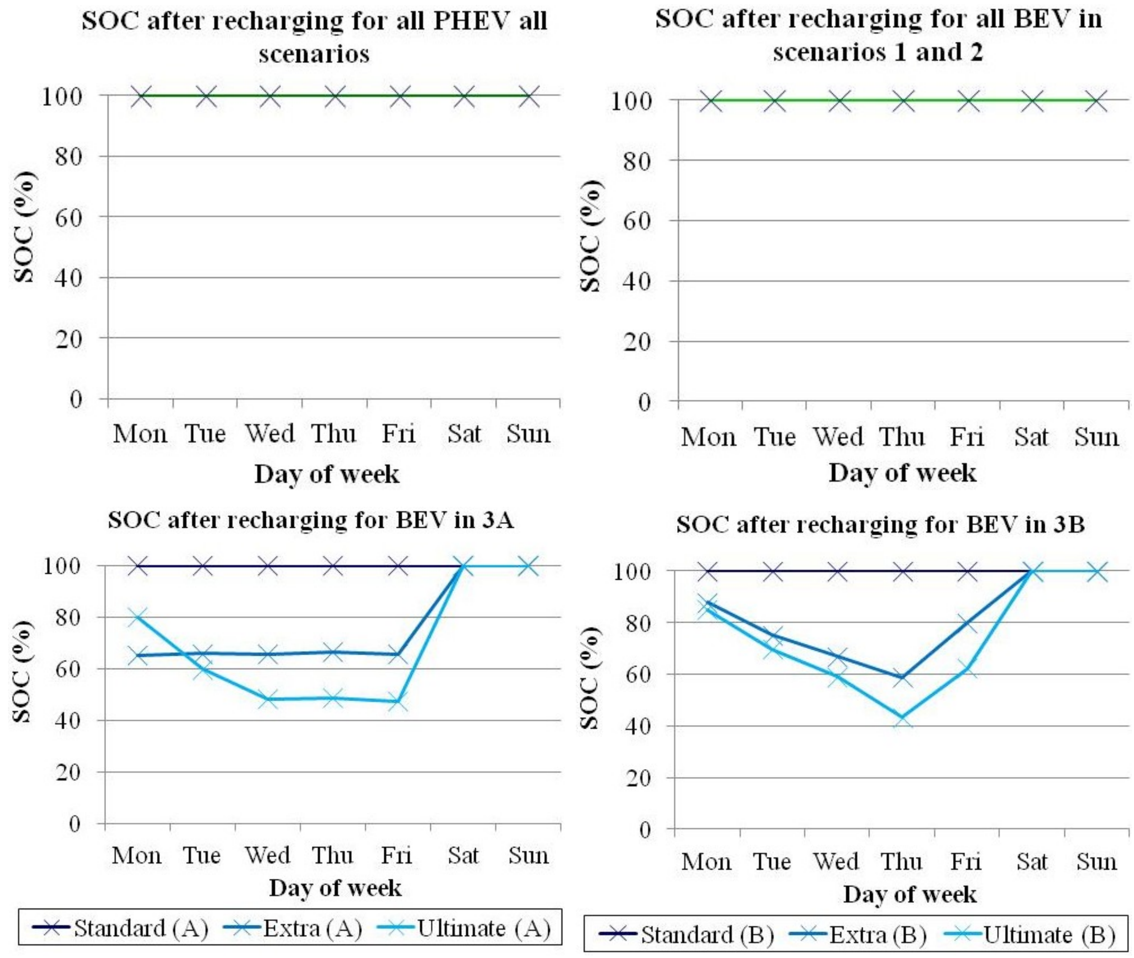


Fig. 8.12. Comparison of SOC remaining after recharging each day of the test week for PHEV in all scenarios (top left) and for BEV in scenarios 1 and 2 (top right), in 3A (bottom left) and 3B (bottom right).

In scenario 3, however, the two variations A and B test alternative methods of shifting BEV recharging loads from workdays to weekends, employing partial recharging to do so. The 50:40:10 split of BEV travelling different mileages was used to divide BEV recharging groups into subgroups by the same ratio to determine the vehicles that are active in load-shifting.

The *Standard* subgroup (BEV travelling the maximum daily mileages on each day) are assumed to require recharging to full every night so SOC after recharging is constant at 100%: no different from 1B and 2B. The *Ultimate* subgroup (BEV travelling average mileages on each day) and the *Extra* subgroup (BEV travelling the average plus the SD mileage on each day) are however permitted deteriorating SOC over the week then recharged to full on the weekend.

8.5.3 DIFFERENCES IN RECHARGING DURATION

Fig. 8.13 shows the difference in recharging durations for BEV and PHEV in the difference Scenarios. PHEV recharge durations were identical across all scenarios. Durations for BEV recharging are identical between scenarios 1A and 2A and between 1B and 2B.

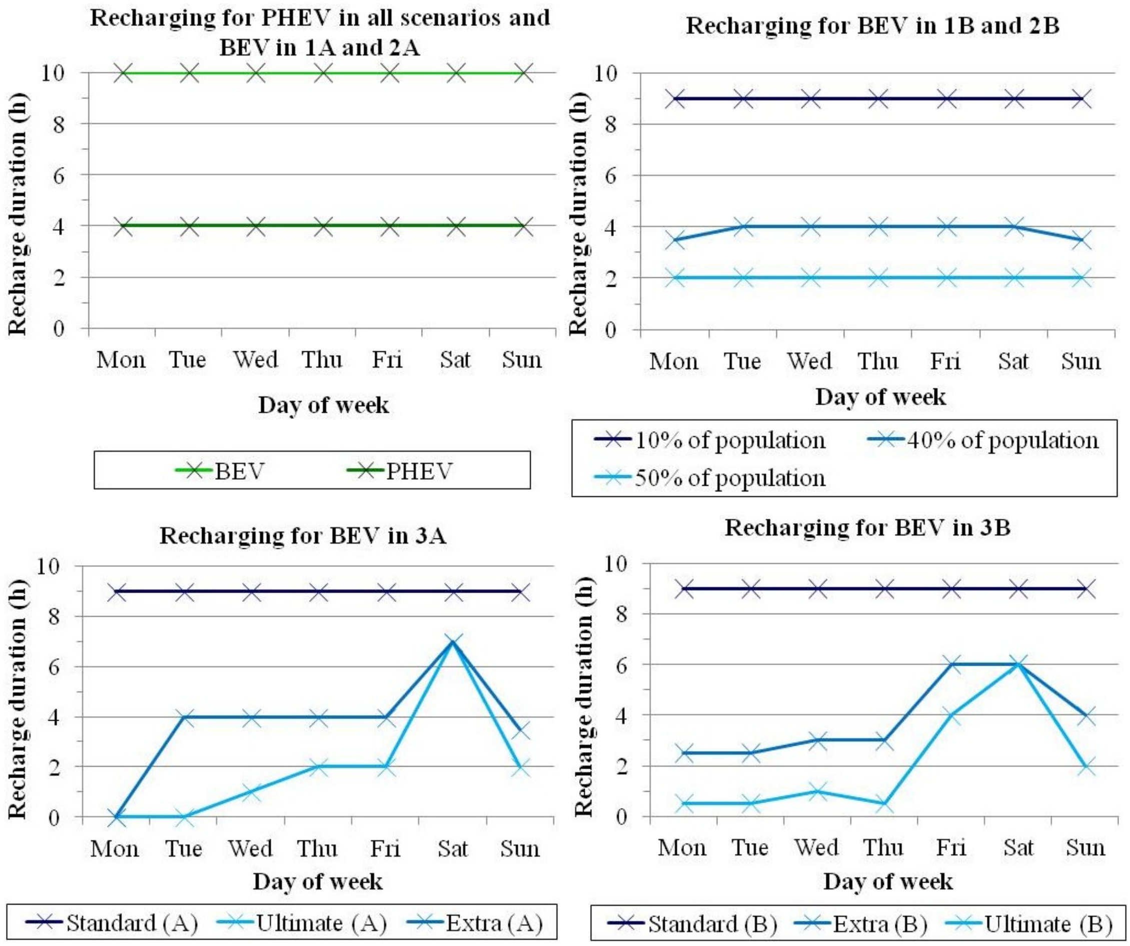


Fig. 8.13. Recharge durations for PHEV in all scenarios and variations (top left) and for BEV in 1A and 2A (top left), in 1B and 2B (top right), in 3A (bottom left) and in 3B (bottom right).

Recharging durations for scenario 3 differ from those in scenarios 1 and 2. They also differ between 3A and 3B. This is not caused by differences in daily mileage which are assumed to be the same for 3A and 3B as for 1B and 2B. It is instead caused by the load-shifting tested in these two variations (although *Standard* subgroups of BEV in both variations are assumed to require 'to-full' recharging – no different from 1B or 2B). *Ultimate* and *Extra* subgroups have had their recharging durations modified through partial recharging in different ways in 3A compared to 3B, as is shown by Fig. 8.14. 3B levels recharging loads over the workday period, and over the weekend and subsequently produces a load profile more complementary to the weekly pattern evident in existing demand highlighted in Chapter 7.

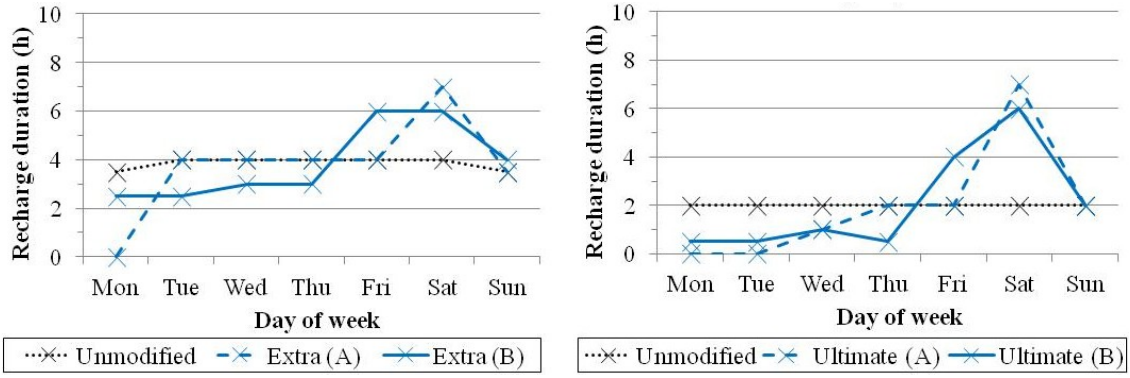


Fig. 8.14. Comparison of daily recharging durations for BEV vehicles in *Extra* subgroups in 3A and 3B (left), and comparison of daily recharging durations for BEV vehicles in *Ultimate* subgroups in 3A and 3B (right). Please note that 'unmodified' represents the recharging durations that vehicles would require if recharged to full every night.

8.6 SCENARIO CONSTRUCTION SUMMARY

Three scenarios have been constructed in this chapter. The Parry Tool brought together:

- A review of specifications for present and imminently available plug-in vehicles in the UK, and
- Vehicle-focused ownership and travel behaviour statistics drawn from the people-focused UK National Travel Survey [1],

...To build recharging loads for plug-in vehicles comprised of two examples plug-in vehicles (BEV and PHEV), to test impacts on existing national electricity demand [8], over a chosen test week. This constituted scenario 1.

The information brought together by the Parry Tool, which also included a review of patterns exhibited by UK national electricity demand, was then used to inform the design of a recharging demand management strategy and load levelling technique: time-block based Recharging Regimes. This constituted scenario 2.

Justification for the time-block approach was provided, citing the lack of a stepping stone between completely unrestricted recharging at the advent of plug-in vehicle adoption, and the heavily third-party regulated recharging monitoring and control mechanisms that are expected to be used when/if plug-in vehicle adoption rises sufficient to cause problems for the electricity generation and supply system and require tighter regulation and scheduling.

The information gathered by the Parry Tool was then used to further inform a more advanced kind of plug-in vehicle recharge scheduling – one that uses partial recharging of vehicle batteries to shift recharging loads from workdays to weekends. This constituted scenario 3.

CHAPTER 9: APPLYING SCENARIOS – ANALYSIS OF RESULTS

The analysis of recharging impacts resulting from the application of the three scenarios constructed for this study is presented in this chapter. Results are provided in two formats: singularly for each scenario variation, then again as a series of comparisons. A discussion will subsequently follow referring to results and to the analysis of impacts upon maxima and minima, in context of considering how the different scenarios have influenced the magnitude, duration, timing and overall shape of demand. This analysis was conducted in Microsoft Excel 2007.

9.1 RESULTS FROM INDIVIDUAL SCENARIO VARIATIONS

Singular results for each scenario are provided below. A graph of electricity demand for the study week without the addition of recharging loads is also supplied at the beginning of this part of Chapter 9 for comparison. These graphs and charts will be referred to in the discussion at the end of this chapter.

9.1.1 EXISTING DEMAND (NO SCENARIOS APPLIED)

The test week chosen for this analysis was the 5th-11th January 2009. Reasons for choice of test week are given at the end of Chapter 7. The demand profile acquired from National Grid [8] for the chosen test week is displayed in Fig. 8.1 and features the annual peak for that year of 58,554 MW occurring at 17:00 h on Tuesday 6th. This is demand as it exists prior to the addition of loads due to the recharging demands of plug-in vehicles tested by the scenarios constructed in the previous chapter. Also shown in Fig. 9.1 is the arbitrary network limit of 60,000 MW, the basis for which is also explained at the end of Chapter 7.

Existing demand variability is shown in Fig. 9.2. Demand varies by 21,558 MW to 24,871 MW on working days Monday to Friday. It varies by less on weekend days: on Saturday demand varies by 18,265 MW, on Sunday by 18,272 MW. Peak demand occurred at 17:00 h on every day of the text week excluding Saturday where it occurred at 17:30 h.

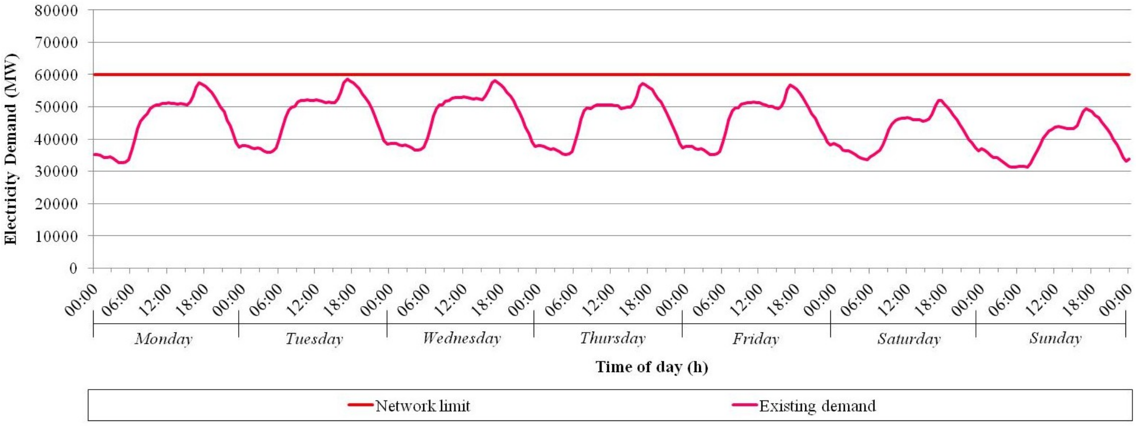


Fig. 9.1. National electricity demand as recorded for the week of highest demand in 2009 (5th – 11th January).

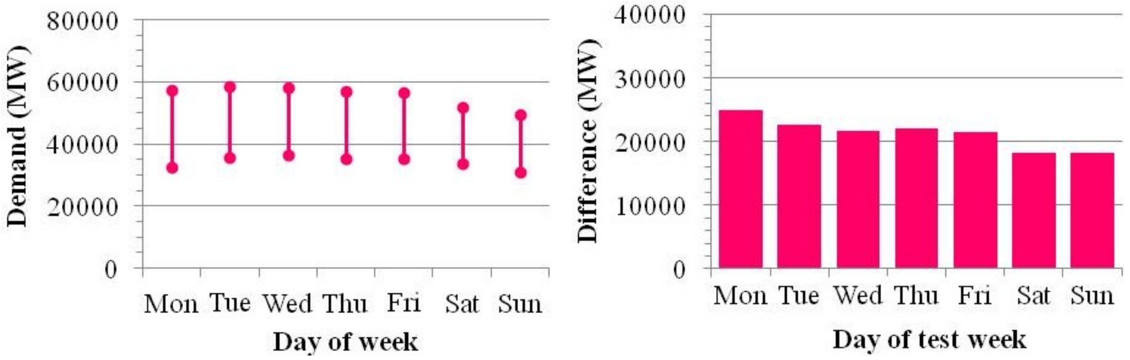


Fig. 9.2. Variability in existing demand as plotted by the range over which demand varied per day between demand maxima and minima (left) and as the absolute difference between maxima and minima per day (right).

9.1.2 SCENARIO 1

Scenario 1 tested the addition of plug-in vehicle recharging loads when it was assumed that vehicles would begin recharging upon arrival home. Variation A assumed all vehicles completely depleted their batteries and so required flat-to-full recharging on every day of the week. Variation B assumed that the BEV population comprised of vehicles travelling different daily mileages.

Specifically 1B assumed that: 50% of the BEV travelled average daily mileages, 40% travelled the average plus SD on each day and 10% travelled the maximum recorded mileage for each day. The resulting load profile for the addition of plug-in vehicles under scenario 1A conditions is given in Fig. 9.3, under scenario 1B in Fig. 9.4.

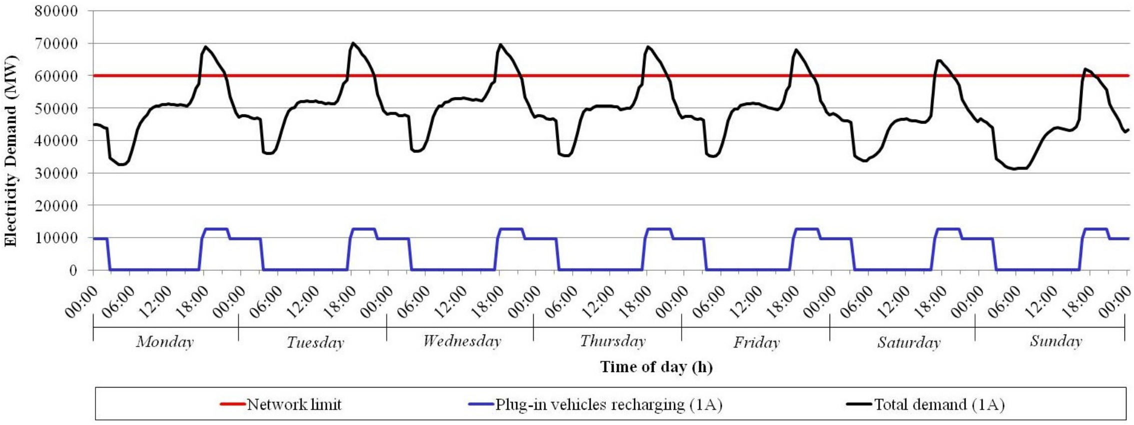


Fig. 9.3. Results from 1A: flat to full recharging for all vehicles, all vehicles recharge upon returning home.

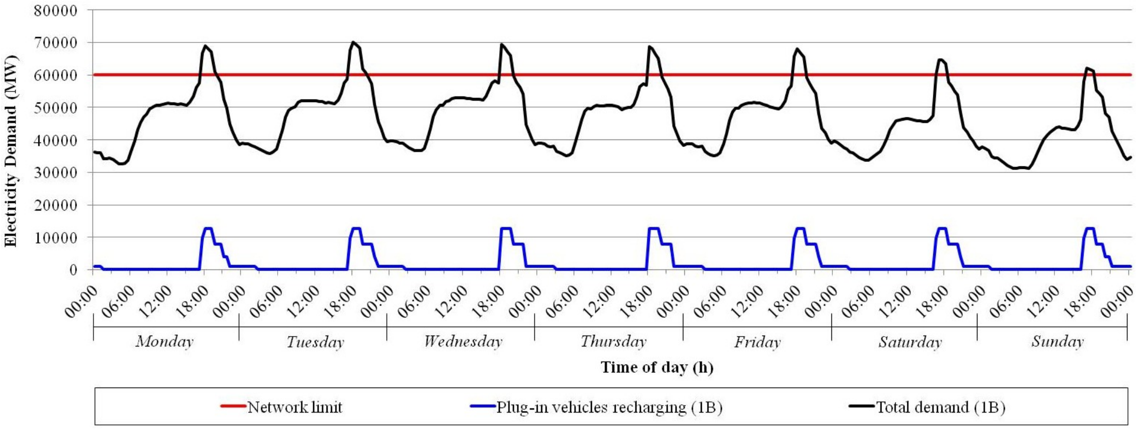


Fig. 9.4. Results from 1B: Flat-to-full recharging assumed for all PHEV, but not for BEV whose recharging is dependent upon daily mileage. All vehicles recharge upon returning home.

In both 1A and 1B the arbitrary network limit of 60,000 MW was breached on every day of the test week. Breaches lasted several hours at a time, the peak magnitudes and durations per day of the week are listed in Table 9-1. The total number of hours over the test week where demand breached the arbitrary network limit was 24.5 h in 1A and 15 h in 1B. Table 9-2 lists by what amount maximum daily demand was increased, provided both in MW and as a percentage of the original peak for each day before recharging loads were applied. The table also lists the timings of the new demand peaks and notes the number of hours by which this has changed.

Fig. 9.5 plots the variability of demand as measured by the difference between daily maxima and minima in two formats: one showing the range over which demand varied per day, the other showing the absolute amount by which demand varied on each day (difference between maximum and minimum demand on each day).

Table 9-1: Breach magnitudes and durations for 1A and 1B.

Day of the test week	Magnitude of breach (MW) – identical for both 1A and 1B	Duration of breach (h)	
		1A	1B
Monday	8929	4.0	2.5
Tuesday	10012	4.0	3.0
Wednesday	9473	4.0	2.0
Thursday	8802	4.0	2.0
Friday	8023	3.5	2.0
Saturday	4577	3.0	2.0
Sunday	2066	2.0	1.5

Table 9-2: Differences in magnitudes and timings of daily maxima in 1A and 1B compared with existing demand.

Day of the test week	Increase in peak demand (MW)	As a percentage increase above existing demand peak (%)	Timing of new demand peak (h past midnight)	Change from existing demand peak time (h)
Monday	11454	19.9	18:00	+1.0
Tuesday	11458	19.6	18:00	+1.0
Wednesday	11247	19.3	18:00	+1.0
Thursday	11628	20.3	18:00	+1.0
Friday	11343	20.0	18:00	+1.0
Saturday	12636	24.3	17:30	No change
Sunday	12636	25.5	17:00	No change

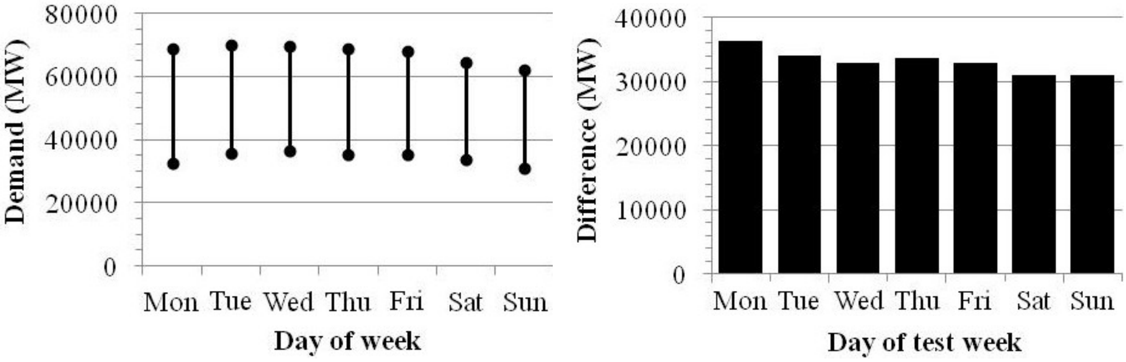


Fig. 9.5. Variability in demand under scenario 1 conditions, as plotted by the range over which demand varied per day between demand maxima and minima (left) and as the absolute difference between maxima and minima per day (right).

9.1.3 SCENARIO 2

Scenario 2 tests the application of overnight Recharging Regimes that shape plug-in vehicle recharging demands to complement the diurnal pattern in existing demand, by splitting vehicles into groups and scheduling each group to begin recharging at a different time. The difference between variation A and B is the same for scenario 2 as it was for scenario 1.

2A like 1A assumed all vehicles completely depleted their batteries and so required flat-to-full recharging on every day of the week. 2B like 1B assumed that the BEV population comprised of vehicles travelling different daily mileages and that travel behaviour across the BEV population was reflected proportionally within each recharging group: 50% of the BEV travelled average daily mileages, 40% travelled the average plus SD on each day and 10% travelled the maximum recorded mileage for each day.

The resulting load profile for the addition of plug-in vehicles under scenario 2A conditions is given in Fig. 9.6 and under scenario 2B conditions in Fig. 9.7. In both 2A and 2B the arbitrary network limit of 60,000 MW was not breached on any day of the test week. The timing of daily peaks and their magnitudes were unchanged by the application of 2A and 2B scenario conditions.

Daily minimum demand however was increased on every day of the test week in both scenario variations, albeit by a greater amount under 2A conditions than under 2B conditions. Table 9-3 lists by what amount daily minimum demand was increased, providing this both in MW and as a percentage of the original peak for each day before recharging loads were applied.

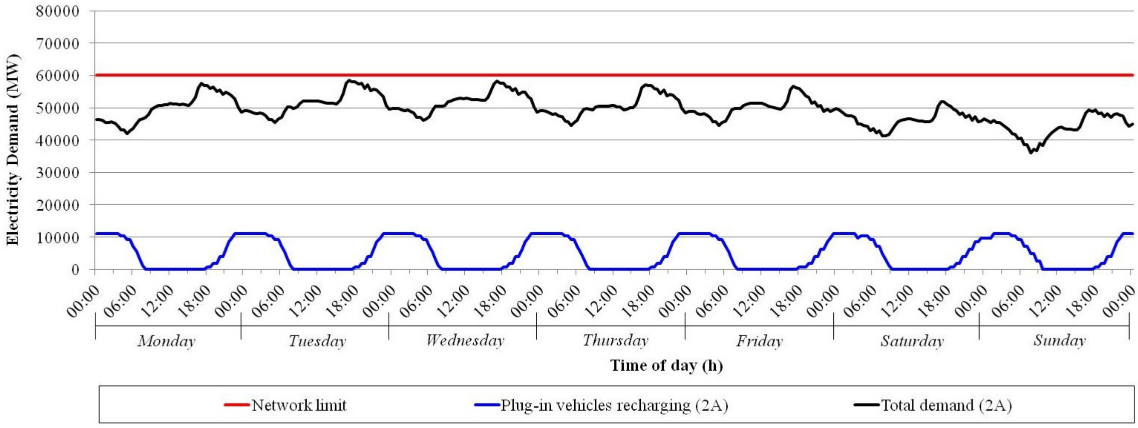


Fig. 9.6. Results from 2A: Flat-to-full recharging assumed for all vehicles, timing of recharging for each day of the week dependent upon specified Recharging Regimes.

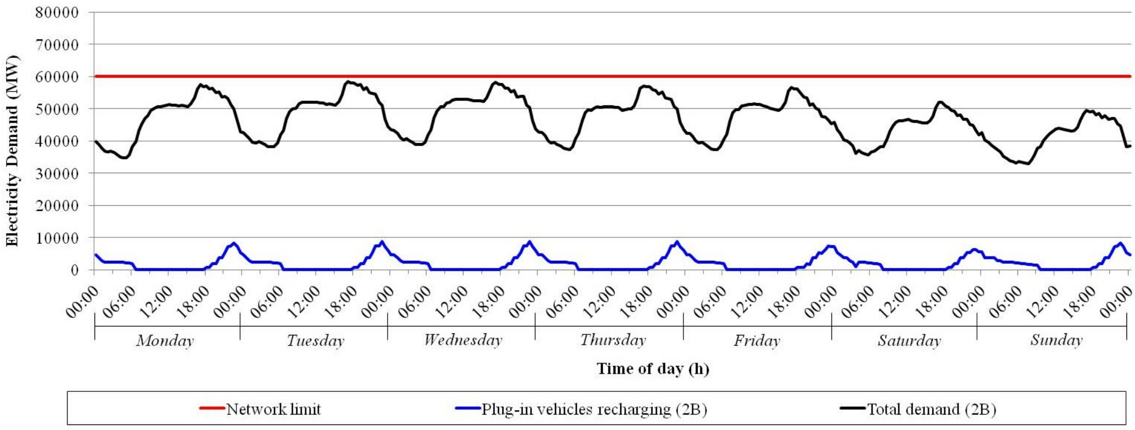


Fig. 9.7. Results from 2B: Flat-to-full recharging assumed for PHEV, but not for BEV. For BEV recharging is dependent upon daily mileage. Timing of recharging for each day of the week dependent upon specified Recharging Regimes.

Table 9-3: Differences in magnitudes of daily minima compared with existing demand, for 2A and 2B.

Day of the test week	Increase in minimum demand (MW)		As a percentage increase above existing demand minimum (%)	
	2A	2B	2A	2B
Monday	9390	2242	28.8	6.9
Tuesday	9520	2272	26.5	6.3
Wednesday	9408	2260	25.7	6.2
Thursday	9399	2251	26.7	6.4
Friday	9422	2272	26.8	6.5
Saturday	7683	2060	22.8	6.1
Sunday	4925	1766	15.8	5.7

The increase of daily minimum demand whilst daily maximum demand remained unchanged resulted in reduction in demand variability. The change is more profound under scenario 2A conditions than under 2B conditions.

Fig. 9.8 shows the variability of demand under 2A conditions, as measured by the difference between daily maxima and minima in two formats: one showing the range over which demand varied per day, the other showing the absolute amount by which demand varied on each day (difference between maximum and minimum demand on each day). Fig. 9.9 shows variability of demand under 2B conditions in the same two formats for comparison.

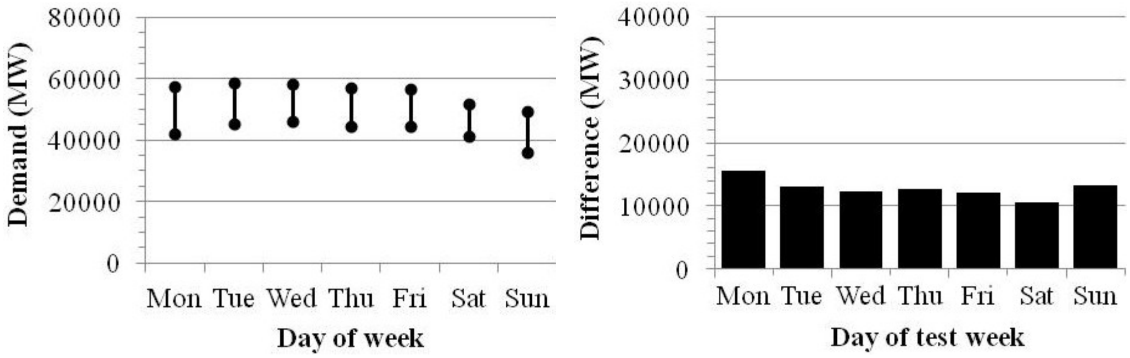


Fig. 9.8. Variability in demand under scenario 2A conditions as plotted by the range over which demand varied per day between demand maxima and minima (left) and as the absolute difference between maxima and minima per day (right).

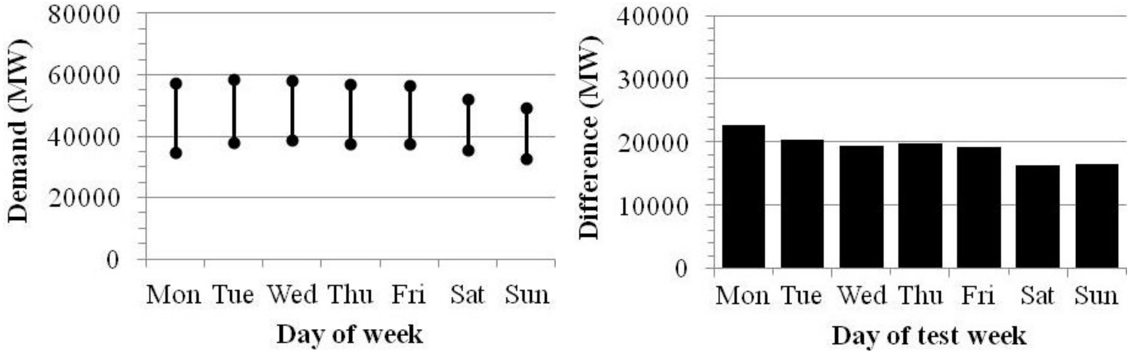


Fig. 9.9. Variability in demand under scenario 2B conditions as plotted by the range over which demand varied per day between demand maxima and minima (left) and as the absolute difference between maxima and minima per day (right).

9.1.4 SCENARIO 3

Scenario 3 tests the application of load-shifting on top of Recharging Regimes to complement the working week pattern in existing demand and further level loads over this period. A basic technique is tested in 3A and a more sophisticated technique tested in 3B that spreads loads more evenly across days where load duration is being taken away and across days where load duration is being added. Scenario 3 adopts the Recharging Regimes of scenario 2 and the assumed daily mileages travelled by BEV in 1B and 2B.

In 3A and 3B the breakdown of travel behaviour for BEV within each recharging group is assumed to be a known quantity, enabling the subdivision of each group based on the three travel behaviours they each comprise into *Ultimate* (average daily mileages), *Extra* (average daily mileages plus SD for each day) and *Standard* (maximum recorded mileage on each day) subgroups. This is in a 50:40:10 ratio as assumed in 1B and 2B, proportionally reflecting the behaviour of the whole BEV population.

In 3A and 3B recharging load durations for BEV are partially decoupled from assumptions of travel behaviour. Vehicles in *Ultimate* and *Extra* subgroups need only recharge their batteries sufficiently to meet their anticipated driving needs for the next day plus 30 miles worth of SOC to accommodate emergency and unplanned travel. The difference between SOC recovered to provide for the next day's driving and the maximum recharging duration a BEV could have had to fully recover their battery SOC to 100% therefore constituted a moveable load, shifted between different days of the week by mandating partial recharging on some days and to-full recharging on others. The resulting load profile for the addition of plug-in vehicles under scenario 3A conditions is given in Fig. 9.10 and under scenario 3B conditions in Fig. 9.11.

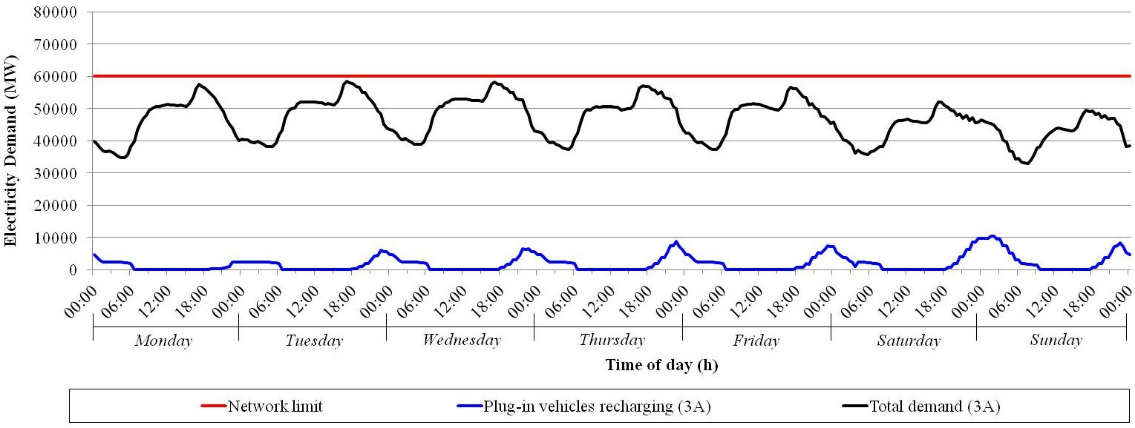


Fig. 9.10. Results from 3A: Flat-to-full recharging assumed for PHEV, but not for BEV. For BEV recharging is partially dependent upon daily mileage but is also dependent upon load-shifting applied to vehicles in *Extra* and *Ultimate* subgroups. Timing of recharging for each day of the week dependent upon Recharging Regimes specified in 2A.

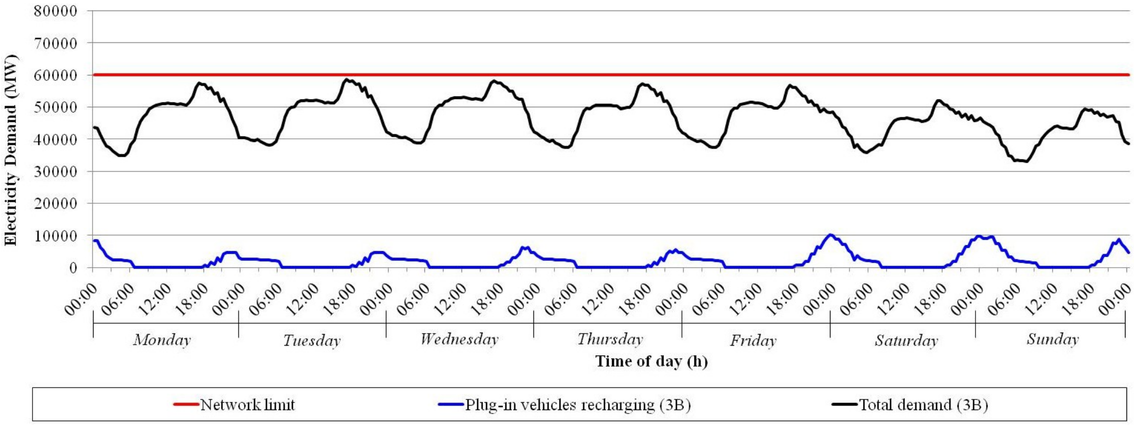


Fig. 9.11. Results from 3B: Conditions are identical to 3A except that load-shifting in this variation has been modified to give a more even spread of loads over days between Monday to Thursday, and a more even spread of loads over days between Friday and Sunday.

In both 3A and 3B the arbitrary network limit of 60,000 MW was not breached on any day of the test week and the timing of daily peaks and their magnitudes were unchanged. Daily minimum demand however was increased on every day of the test week in both scenario variations. This was by the same amount in both scenarios, and by the same amount as under the conditions of 2B. Table 9-4 lists by what amount daily minimum demand was increased (these being the identical for 3A and 3B and also identical with 2B – see Table 9-3), both in MW and as a percentage of the original peak for each day before recharging loads were applied.

Fig. 9.12 shows the variability of demand under scenario conditions for 3A and 3B, again identical with that under conditions for 2B (see Fig. 9.9), as measured by the difference between daily maxima and minima in two formats: one showing the range over which demand varied per day, the other showing the absolute amount by which demand varied on each day (difference between maximum and minimum demand on each day).

Table 9-4: Differences in magnitudes of daily minima compared with existing demand, for 3A and 3B, identical to those of 2B in Table 9-3.

Day of the test week	Increase in minimum demand (MW)	As a percentage increase above existing demand minimum (%)
Monday	2242	6.9
Tuesday	2272	6.3
Wednesday	2260	6.2
Thursday	2251	6.4
Friday	2272	6.5
Saturday	2060	6.1
Sunday	1766	5.7

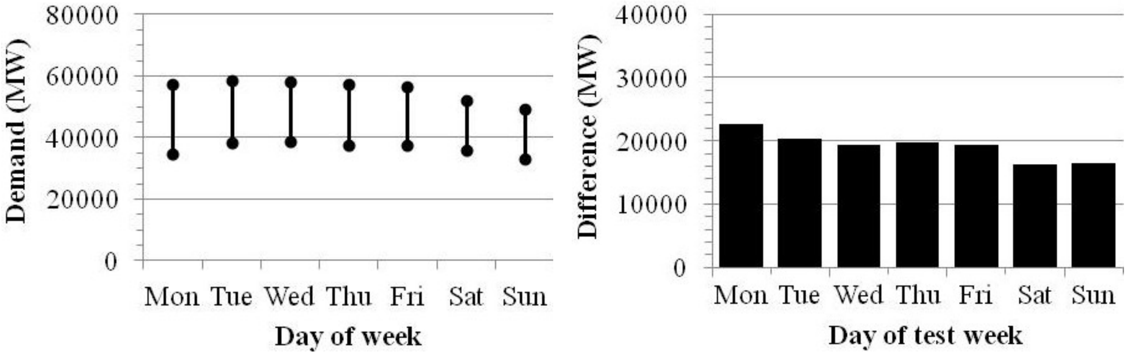


Fig. 9.12. Variability in demand under 3A and 3B conditions as plotted by the range over which demand varied per day between demand maxima and minima (left) and as the absolute difference between maxima and minima per day (right). Variability as plotted here for 3A and 3B is identical to that under 2B conditions in Fig. 9.9.

9.2 RESULTS COMPARISONS

To better analyse results, graphs and charts are provided in this part of Chapter 9 that plot results for different scenario variations together. Comparison of scenarios 1 and 2 describes the impact of unrestricted recharging versus recharging that has been restricted by the implementation of Recharging Regimes. Comparison of variations within scenarios 1 and 2 (comparing 1A to 1B, or 2A to 2B) meanwhile shed light on the sensitivity of those scenarios to changing assumptions about BEV travel behaviour.

Scenario 3 shares vehicle daily mileage behaviour characteristics with B variations of scenario 1 and 2, making 3A and 3B comparable only to each other or to 1B or 2B. Comparing scenario 3A and 3B to scenario 2B shows the impacts of load-shifting, applied after Recharging Regimes are in place. Comparison of 3A and 3B describes the difference made by altering load-shifting to spread loads more evenly. Comparing 1B to 2B and 3B shows the evolution of the process of applying Recharging Regimes then applying the more advanced load-shifting technique to fully take advantage of both the diurnal and the weekly pattern exhibited by existing demand.

Please note: High and low charts plotting variability as ranged values between demand maxima and minima per day are included here but these are just repeats of the charts given for singular scenario variations. It was unfortunately not possible in Microsoft Excel 2007 to combine them for more direct comparisons so instead they have been shown side by side. A small summary of notable similarities and differences will also be provided but a more general discussion of the impacts of different scenarios and their variations is given at the end of this chapter as is a summary of findings.

9.2.1 UNRESTRICTED RECHARGING VERSUS RECHARGING REGIMES

As noted in the introduction to this part of Chapter 9, the impact upon demand profiles of unrestricted recharging versus the application of Recharging Regimes is shown by the comparison between scenarios 1 (unrestricted recharging) and 2 (Recharging Regimes applied).

9.2.1.1 Comparing 1A to 2A

Under unrestricted recharging conditions in 1A, the arbitrary network limit of 60,000 MW is breached but under restricted recharging conditions in 2B, it is not (see Fig. 9.13). In Fig. 9.14 it can be seen that the difference between maximum and minimum demand increases under scenario 1 conditions but decreases under scenario 2 conditions, relative to that of existing demand.

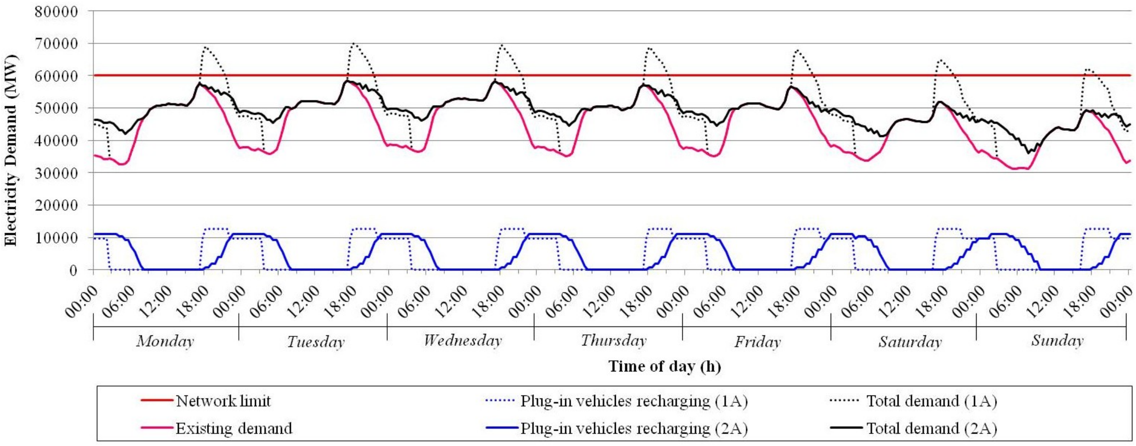


Fig. 9.13. Results comparison of 1A to 2A plotted over existing demand, showing the impact of applying Recharging Regimes.

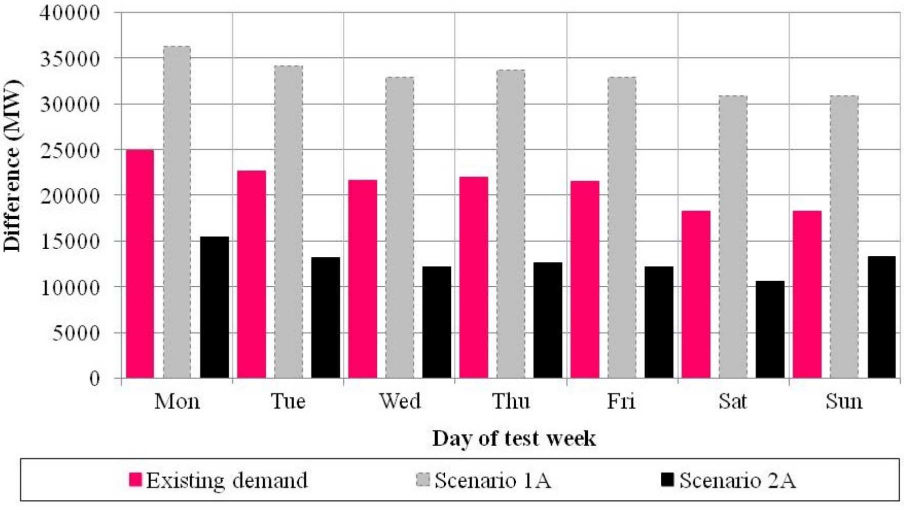


Fig. 9.14. Variability in existing demand and demand under the conditions of scenarios 1A versus 2A, as plotted by the absolute difference between daily maxima and minima.

Fig. 9.15 shows that the difference between daily demand maxima and minima increased in scenario 1A, and that this is because plug-in vehicle recharging loads raised daily maximum demand (daily minimum demand unaffected). Fig. 9.16 shows that the difference between daily demand maxima and minima in scenario 2A decreased, and that this is because plug-in vehicle recharging raised daily minimum demand (daily maximum demand unaffected).

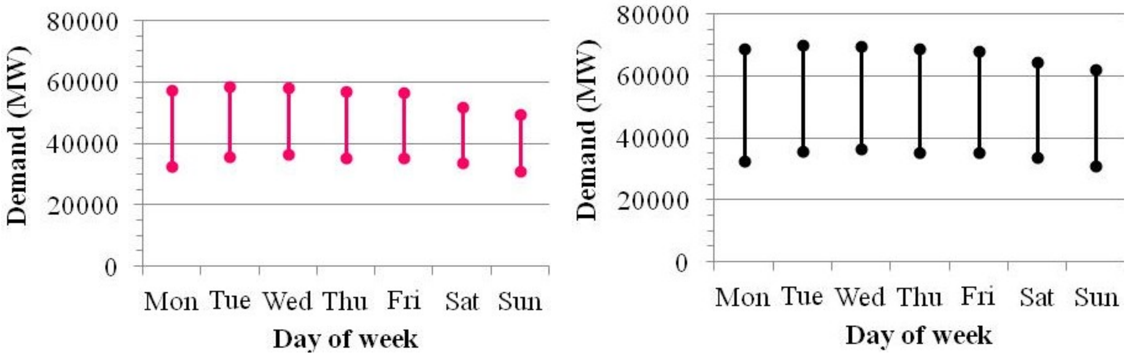


Fig. 9.15. Variability of existing demand (left) compared to variability of demand under the conditions of scenario 1A (right), as plotted by the range over which demand varied per day between demand maxima and minima.

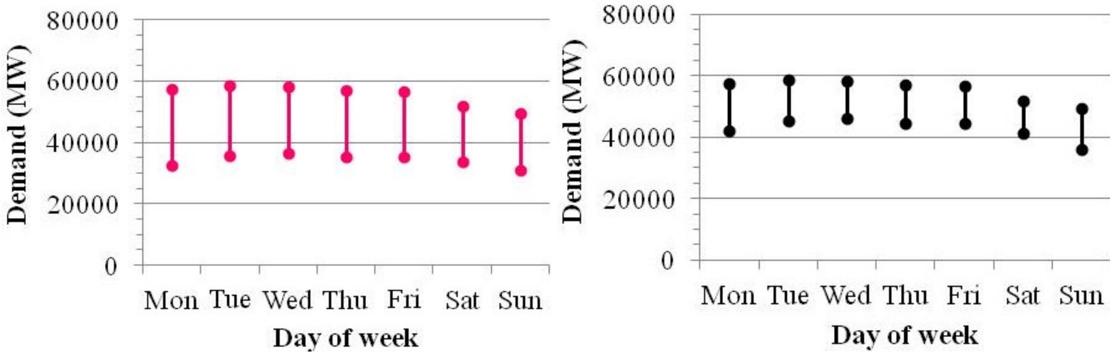


Fig. 9.16. Variability of existing demand (left) compared to variability of demand under the conditions of scenario 2A (right), as plotted by the range over which demand varied per day between demand maxima and minima.

9.2.1.2 Comparing 1B to 2B

Under unrestricted recharging conditions in 1B, the arbitrary network limit of 60,000 MW is breached but under restricted recharging conditions in 2B, it is not (see Fig. 9.17). In Fig. 9.18 it can be seen that the difference between maximum and minimum demand increases under scenario 1 conditions but decreases under scenario 2 conditions, relative to that of existing demand.

Fig. 9.19 shows that the widening of the gap between daily maxima and minima relative to that of existing demand in scenario 1B, arose as a result of plug-in vehicle recharging raising daily maximum demand whilst not affecting daily minimum demand. Fig. 9.20 shows that the narrowing of the gap between daily maxima and minima relative to that of existing demand in scenario 2B, arose as a result of plug-in vehicle recharging raising daily minimum demand whilst not affecting daily maximum demand.

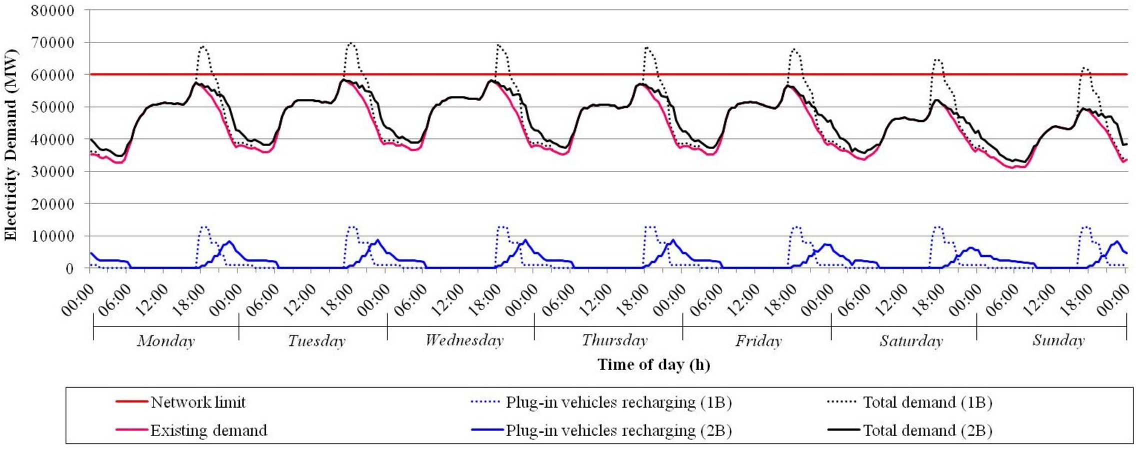


Fig. 9.17. Results comparison of 1B to 2B plotted over existing demand, showing the impact of applying Recharging Regimes.

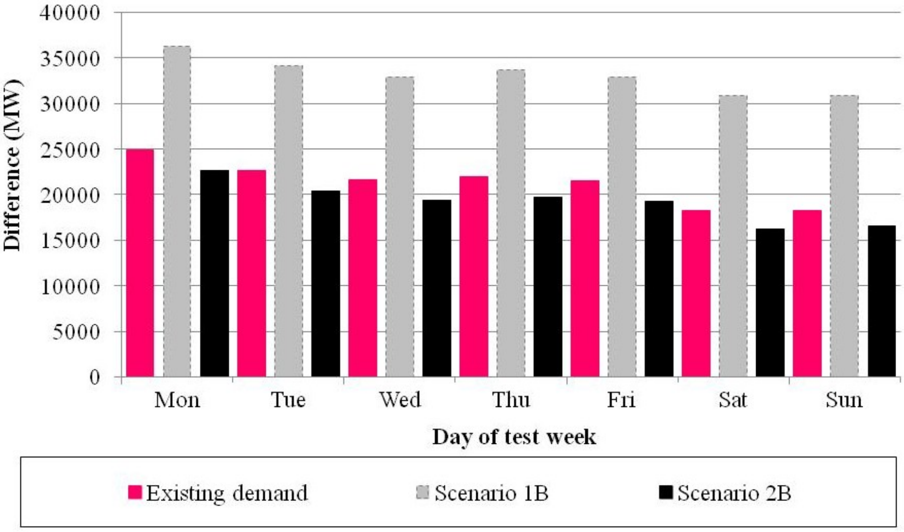


Fig. 9.18. Variability in existing demand and demand under the conditions of scenarios 1B versus 2B, as plotted by the absolute difference between daily maxima and minima.

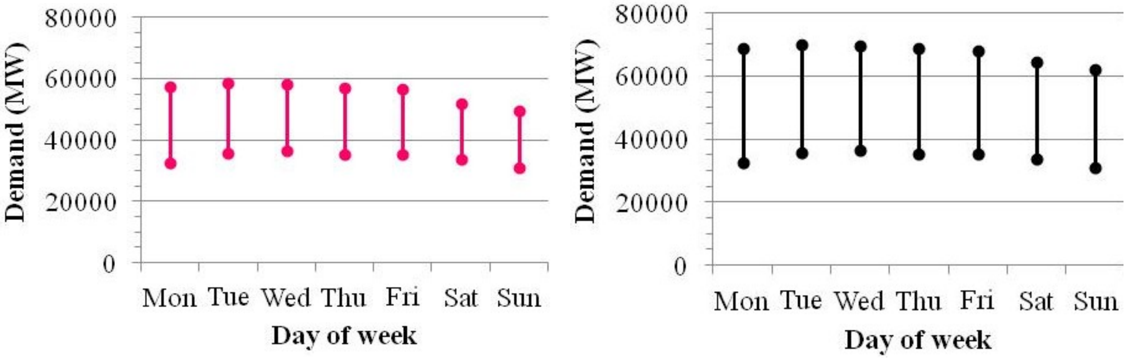


Fig. 9.19. Variability of existing demand (left) compared to variability of demand under the conditions of scenario 1B (right), as plotted by the range over which demand varied per day between demand maxima and minima.

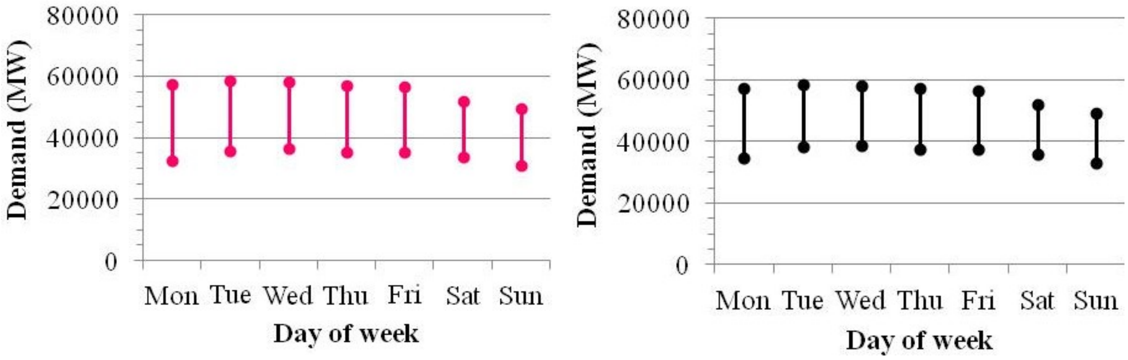


Fig. 9.20. Variability of existing demand (left) compared to variability of demand under the conditions of scenario 2B (right), as plotted by the range over which demand varied per day between demand maxima and minima.

9.2.2 CHANGING ASSUMPTIONS ABOUT VEHICLE DAILY MILEAGES

As noted in the introduction to this part of Chapter 9, the impact upon demand profiles of changing assumptions about vehicle recharging needs based on daily mileages travelled, is shown by the comparison between variations A and B of scenarios 1 and 2. 1A and 2A assuming all vehicles require flat-to-full recharging, 1B and 2B assuming the BEV population comprises 3 groups of vehicles adopting different daily mileage patterns.

9.2.2.1 Comparing 1A to 1B

Under unrestricted recharging conditions in 1A, the arbitrary network limit of 60,000 MW is breached on every day and changing assumptions about BEV daily mileages does not change this (see Fig. 9.21). As can also be seen from the figure however, the adoption of more realistic daily mileage patterns for BEV in 1B makes the plug-in vehicle demand curve sharper either side of the peak. This is because duration of plug-in vehicle loads for BEV are affected and if all vehicles start recharging at roughly the same time, there is a sharp rise to the peak followed by a tailing off of demand, the gradient for which is determined by the number of vehicles that complete recharging over a given time period.

In Fig. 9.22 it can be seen that the difference between maximum and minimum demand increases relative to that of existing demand by the same amount regardless of the change in assumptions about BEV daily mileages between 1A and 1B. Fig. 9.23 shows that the widening of the gap between daily maxima and minima relative to that of existing demand arose in both 1A and 1B as a result of plug-in vehicle recharging raising daily maximum demand, whilst daily minimum demand was unaffected.

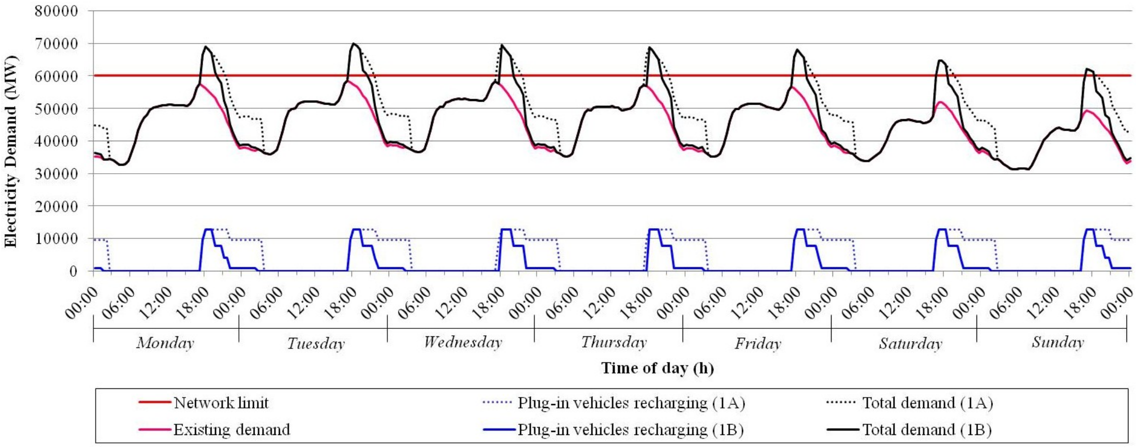


Fig. 9.21. Results comparison of 1A to 1B plotted over existing demand, showing the impact of changing assumptions about daily vehicle mileages.

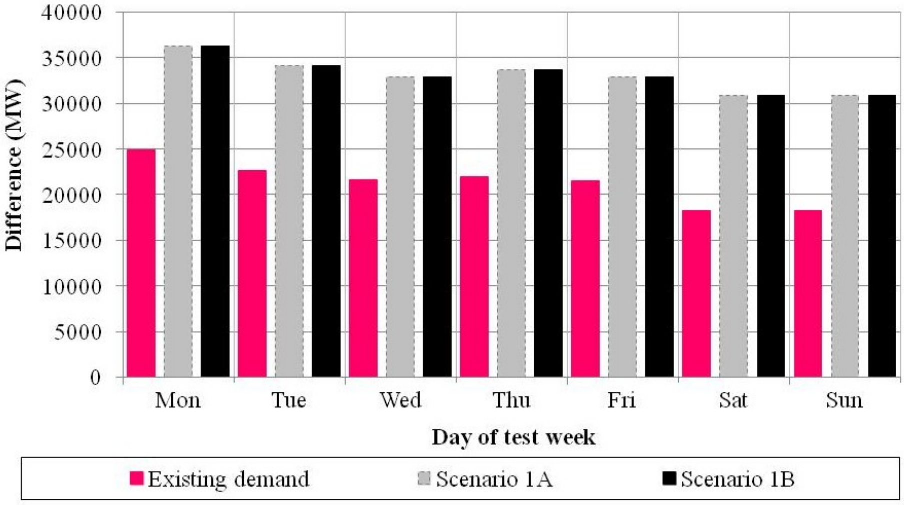


Fig. 9.22. Variability in existing demand and in demand under conditions of scenarios 1A versus 1B, as plotted by the absolute difference between daily maxima and minima.

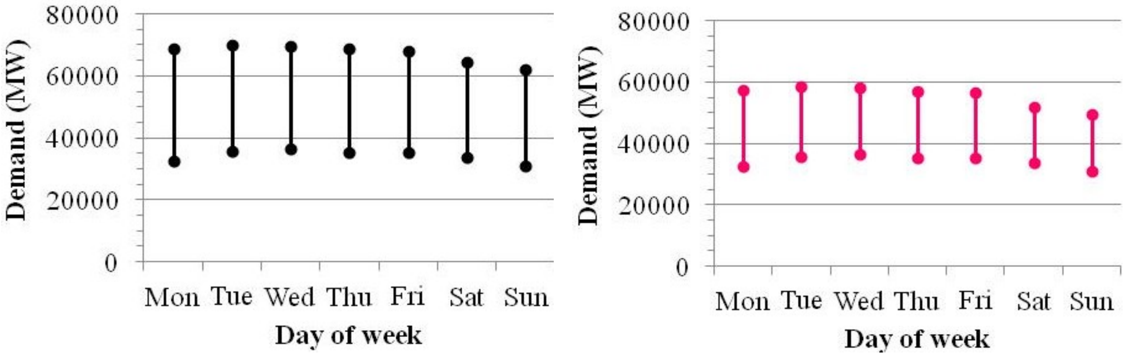


Fig. 9.23. Variability of demand under the conditions of scenario 1A and 1B (left) compared to variability of existing demand (right), as plotted by the range over which demand varied per day between demand maxima and minima.

9.2.2.2 Comparing 2A to 2B

Under scenario 2 conditions, where Recharging Regimes are applied and unrestricted recharging prevented, no breach of the arbitrary network limit of 60,000 MW occurs. Changing the assumptions about daily vehicle mileages and therefore recharging needs does, however, change the duration of plug-in vehicle recharging loads and so changes the shape of the resulting demand curve in a similar way to that of scenario 1, making 2B the sharper profile than 2A (see Fig. 9.24).

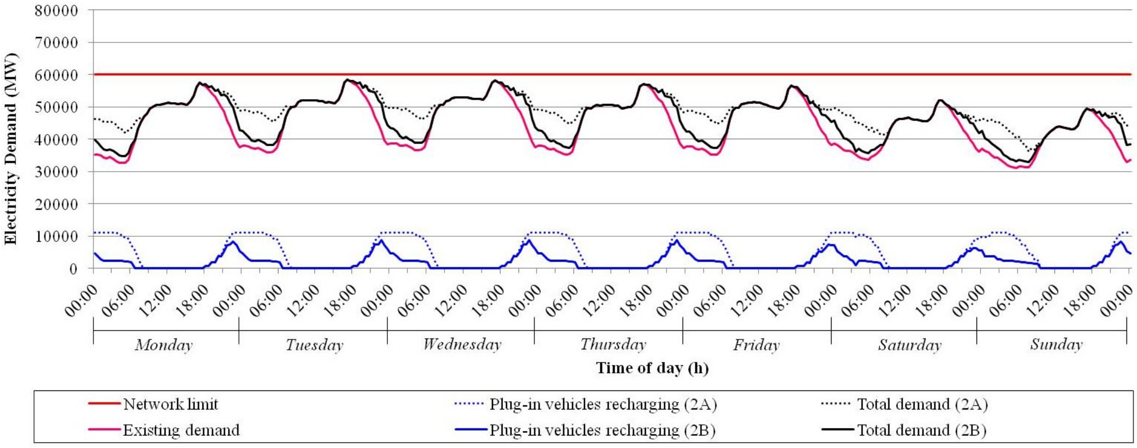


Fig. 9.24. Results comparison of 2A to 2B plotted over existing demand, showing the impact of changing assumptions about daily vehicle mileages.

In Fig. 9.25 it can be seen that the difference between daily demand maxima and minima decreases relative to that of existing demand in both 2A and 2B. Fig. 9.25 and Fig. 9.26 show that this reduction is strongest when it is assumed that all vehicles require daily flat-to-full recharging in 2B. In both 2A and 2B, the narrowing of the gap between daily maxima and minim arose because the magnitude of the daily demand minima was increased. Daily demand maxima (peaks) were unaffected in both variations (see Fig. 9.27 and 9.28).

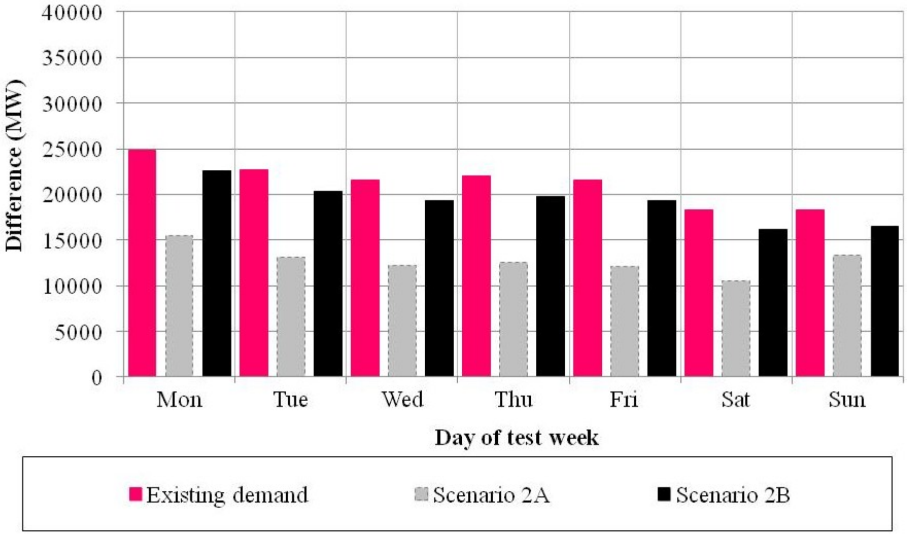


Fig. 9.25. Variability in existing demand and in demand under the conditions of scenarios 2A and 2B, as plotted by the absolute difference between daily maxima and minima.

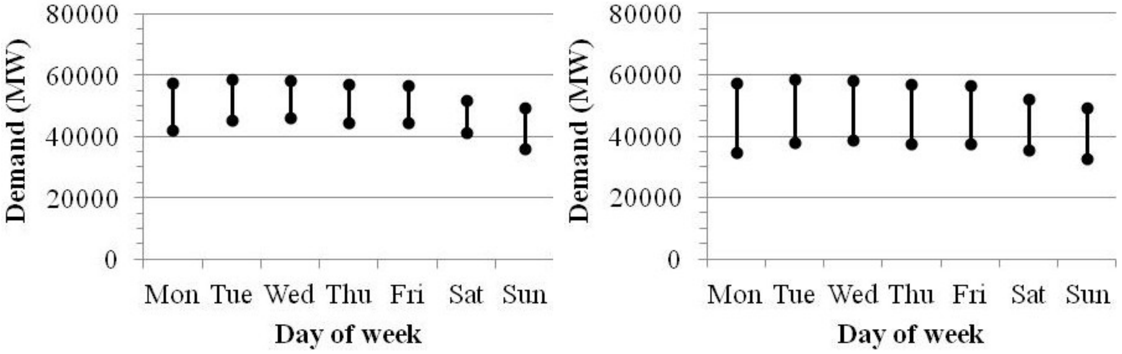


Fig. 9.26. Variability in demand under scenario 2A (left) and 2B (right) conditions, as plotted by the range over which demand varied per day between demand maxima and minima.

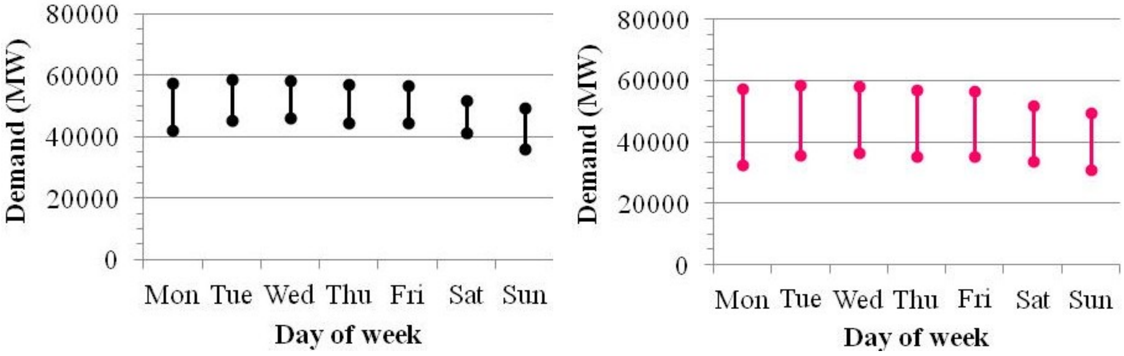


Fig. 9.27. Variability of demand under the conditions of scenario 2A (left) compared to variability of existing demand (right), as plotted by the range over which demand varied per day between demand maxima and minima.

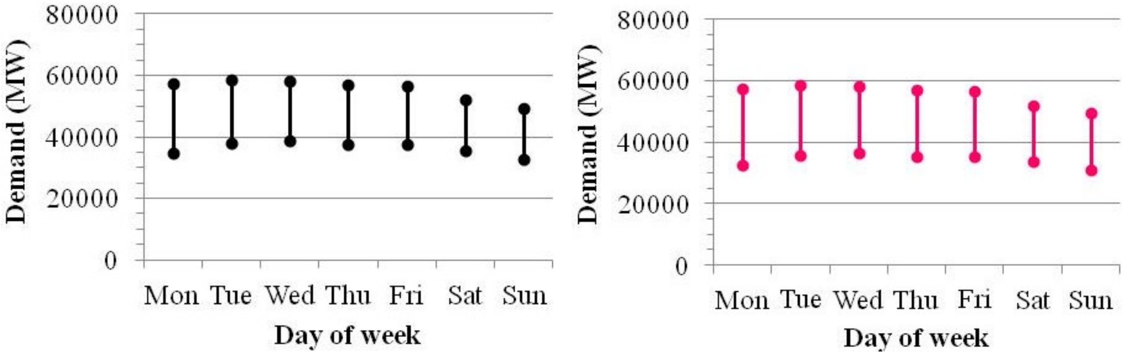


Fig. 9.28. Variability of demand under the conditions of scenario 2B (left) compared to variability of existing demand (right), as plotted by the range over which demand varied per day between demand maxima and minima.

9.2.3 CONSIDERING IMPACTS OF LOAD-SHIFTING

As noted in the introduction to this part of Chapter 9, scenario 3 considers the application of load-shifting on top of the implementation of Recharging Regimes. The first comparison made will is between 2B, which employs Recharging Regimes only, and 3A, which considers the most basic form of load-shifting. Next will be a comparison between 3A, the basic concept of load-shifting, and 3B, a more complex form of load-shifting.

Lastly a comparison between 1B, 2B and 3B will show the potential evolution of plug-in vehicle recharging from worst to best case scenario: from unrestricted recharging, to recharging restricted by Recharging Regimes in order to level demand over the diurnal pattern in existing demand, to recharging restricted by Recharging Regimes coupled to load-shifting measures in order to level demand over the diurnal and working week patterns in existing demand.

9.2.3.1 Comparing 2B to 3A

The arbitrary network limit of 60,000 MW was not breached in 2B or 3A, due to the restricted recharging conditions applied to both by Recharging Regimes (see Fig. 9.29). Load-shifting applied in 3A is most visible in Fig. 9.29 on Monday night and Tuesday night where load has been shaved off and Saturday night where loads have been deposited.

The amount of load shifted per day of the week in 3A results from changing of load durations for recharging and thus daily recharging loads of vehicles in *Ultimate* and *Extra* subgroups, as demonstrated by Tables 9-5 and 9-6. In Table 9-7 total daily loads for BEV and for all plug-in vehicles together are given for 2B and 3A. The net shifting of loads from and to different days of the week is provided in MWh and as a percentage of total plug-in vehicle loads per day of the test week. Compared to 2B, 3A removed 75,136 MWh of load from workdays (Monday to Wednesday) deposited 71,283 MWh of load on Saturday.

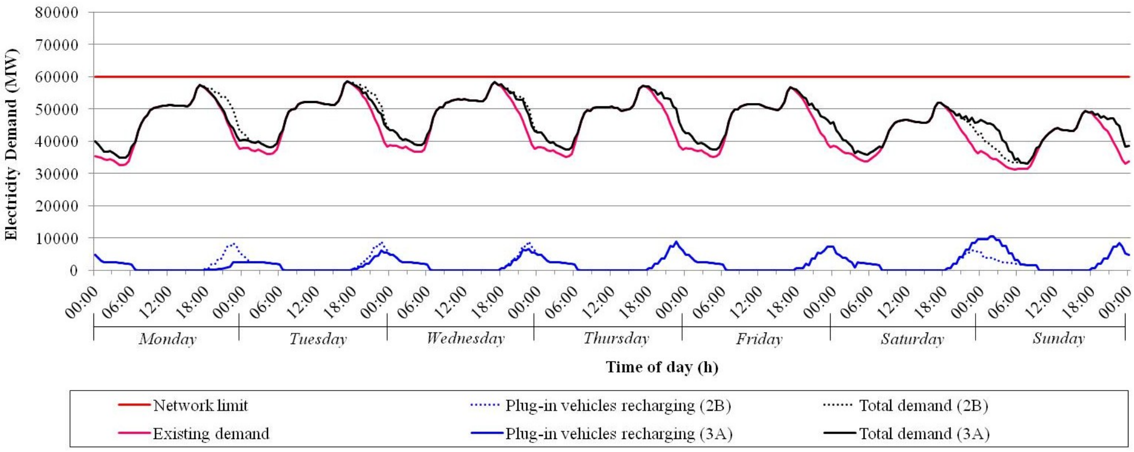


Fig. 9.29. Results comparison of 2B to 3A plotted over existing demand, showing the impact of changing assumptions about daily vehicle mileages.

Table 9-5: Relative differences made to recharging durations and loads by the application of load-shifting in 3A versus 2B, for vehicles travelling average daily mileages (50% of BEV population in 2B, labelled subgroup *Ultimate* in 3A).

Day of the test week	Load duration (h)		Load duration change[1] (h)	Daily load (MWh)		Net change in load[3] (MWh)
	2B	3A		2B	3A	
Mon	2.0	0.0	-2.0	19266	0	-19266
Tue	2.0	0.0	-2.0	19266	0	-19266
Wed	2.0	1.0	-2.0	19266	9633	-9633
Thu	2.0	2.0	0.0	19266	19266	0
Fri	2.0	2.0	0.0	19266	19266	0
Sat	2.0	7.0	+5.0	19266	67430	+48164
Sun	2.0	2.0	0.0	19266	19266	0
Weekly totals	**14.0**	**14.0**	**0.0**	**134859**	**134859**	**0**

[1] Load duration change calculated as load duration in 3A minus load duration in 2B.

[2] Recharging loads calculated by dividing the recharging rate for BEV specified in Chapter 5 (2.4kWh) by 1000 so as to be in MW/h, then multiplying this by the net change in recharging load duration in hours, then by the number of vehicles to which the change applied (50% of the BEV population fall within subgroup *Ultimate*: 4,136,666 vehicles).

[3] Net change in daily recharging load calculated as daily load for 3A minus daily load for 2B.

Please note a discrepancy has been introduced in 3A: in Table 9-6 vehicles in *Extra* subgroups appear to be recharging for half an hour less over the week following modification, compared to 2B for vehicles travelling the same daily mileages. This is due to rounding recharging need to the nearest half hour based on daily mileages instead of the weekly total required, then being distributed over the days of the week in 1B, 2B, 3A and 3B. As a result, it appears that total plug-in vehicle demand has decreased by 1%. Details for how this came about can be found in Appendix 3, but the issue will be further discussed in the project evaluation.

Table 9-6: Relative differences made to recharging durations and loads by the application of load-shifting in 3A versus 2B, for vehicles travelling average plus SD daily mileages (40% of BEV population in 2B, labelled subgroup *Extra* in 3A).

Day of the test week	Load duration (h)		Load duration change[1] (h)	Daily load (MWh)		Net change in load[3] (MWh)
	2B	3A		2B	3A	
Mon	3.5	0.0	-3.5	26972	0	-26972
Tue	4.0	4.0	0.0	30825	30825	0
Wed	4.0	4.0	0.0	30825	30825	0
Thu	4.0	4.0	0.0	30825	30825	0
Fri	4.0	4.0	0.0	30825	30825	0
Sat	4.0	7.0	+3.0	30825	53944	+23119
Sun	3.5	3.5	0.0	26972	26972	0
Weekly totals	**27.0**	**26.5**	**-0.5**	**208068**	**204215**	**-3853**

[1] Load duration change calculated as load duration in 3A minus load duration in 2B.

[2] Recharging loads calculated by dividing the recharging rate for BEV specified in Chapter 5 (2.4kWh) by 1000 so as to be in MW/h, then multiplying this by the net change in recharging load duration in hours, then by the number of vehicles to which the change applied (40% of the BEV population fall within subgroup *Extra*: 3,210,933 vehicles).

[3] Net change in daily recharging load calculated as daily load for 3A minus daily load for 2B.

Table 9-7: Net BEV daily loads in 3A versus 2B. Load shifted provided in MWh but also as a percentage of total plug-in vehicle recharging loads per day.

Day of the test week	Net BEV load (MWh)		Total Plug-in vehicle load (MWh)		Net load shifted (h)	Percentage of total plug-in load shifted (%)
	2B	3A	2B	3A		
Mon	63576	17339	66579	20342	-46237	-69
Tue	67430	48164	70432	51167	-19266	-27
Wed	67430	57797	70432	60799	-9633	-14
Thu	67430	67430	70432	70432	0	0
Fri	67430	67430	70432	70432	0	0
Sat	67430	138712	70432	141715	+71283	+101
Sun	63576	63576	66579	66579	0	0
Weekly totals	**464301**	**460448**	**485319**	**481466**	**-3853**	**-1**

In Fig. 9.30 it can be seen that the difference between maximum and minimum demand under 3A conditions is identical to the difference between maximum and minimum demand under 2B conditions. There is however a decrease in the difference between maximum and minimum demand relative to that of existing demand. Fig. 9.31 shows that the narrowing of the gap between daily maxima and minima relative to that of existing demand arose in both 2B and 3A as a result of plug-in vehicle recharging raising daily minimum demand (by the same amount in both scenarios), whilst daily maximum demand was unaffected.

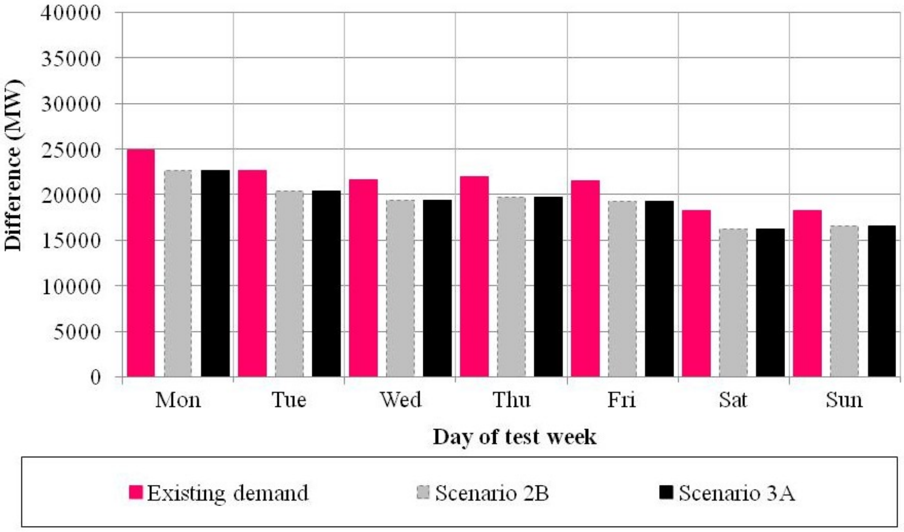


Fig. 9.30. Variability in existing demand and in demand under the conditions of scenarios 2B and 3A, as plotted by the absolute difference between daily maxima and minima.

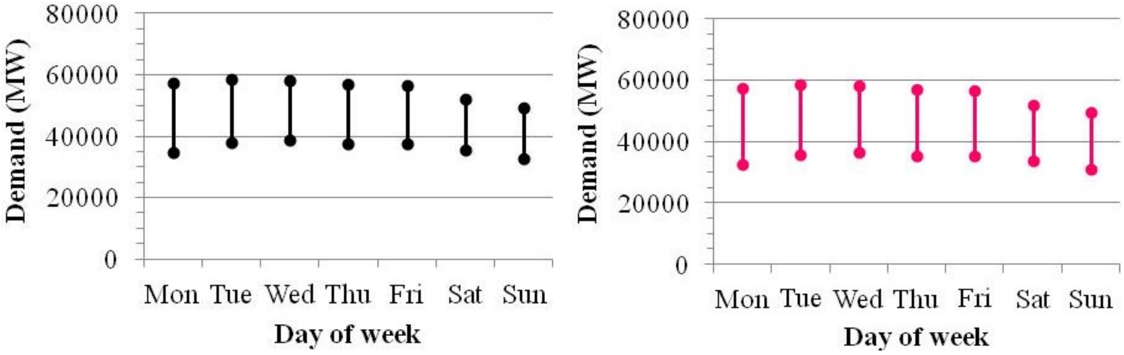


Fig. 9.31. Variability of demand under the conditions of scenario 2B and 3A (left) compared to variability of existing demand (right), as plotted by the range over which demand varied per day between demand maxima and minima.

9.2.3.2 Comparing 3A to 3B

The arbitrary network limit of 60,000 MW was not breached in 3A or 3B, due to the restricted recharging conditions applied to both by Recharging Regimes (see Fig. 9.32) identical to those used in scenario 2. Differences in load-shifting applied in 3A and 3B are most visible in Fig. 9.32 on Thursday night and Saturday night where loads have been shaved off and on Friday night and Monday morning (Sunday night) where loads have been deposited.

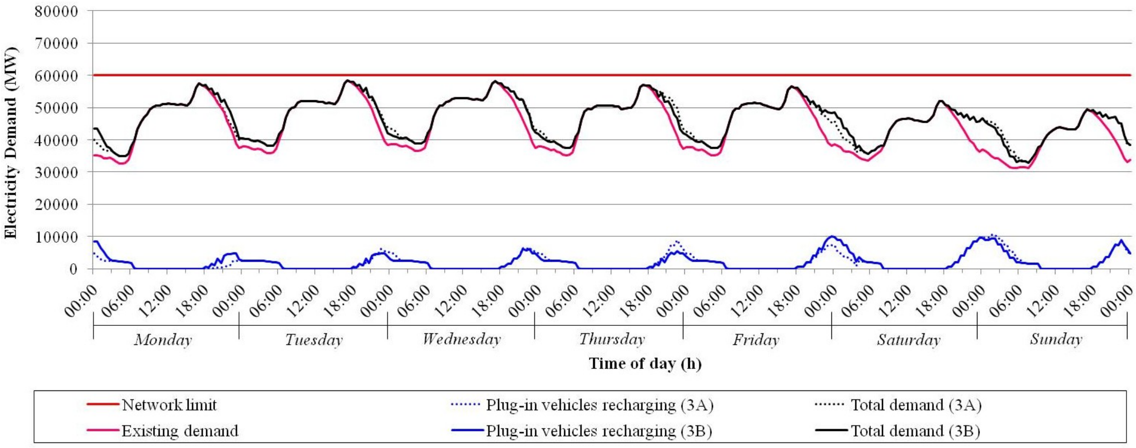


Fig. 9.32. Results comparison of 3B to 3A plotted over existing demand, showing the impact of changing assumptions about daily vehicle mileages.

The amount of load shifted per day of the week results from changing load durations for recharging, and thus daily recharging loads of vehicles in *Ultimate* and *Extra* subgroups in 3A and 3B. Differences in load-shifting applied in 3A and 3B are detailed in Tables 9-8 and 9-9. In Table 9-10 total daily loads for BEV and for all plug-in vehicles together are given for 3A and 3B. The net shifting of loads from and to different days of the week is provided in MWh and as a percentage of total plug-in vehicle loads per day of the test week.

Table 9-8: Relative differences made to recharging durations and loads by the application of load-shifting in 3A and 3B for vehicles travelling average daily mileages (subgroup *Ultimate*).

Day of the test week	Load duration (h)		Load duration change[1] (h)	Daily load (MWh)		Net change in load[3] (MWh)
	3A	3B		3A	3B	
Mon	0.0	0.5	+0.5	0	4816	+4816
Tue	0.0	0.5	+0.5	0	4816	+4816
Wed	1.0	1.0	0.0	9633	9633	0
Thu	2.0	0.5	-1.5	19266	4816	-14449
Fri	2.0	4.0	+2.0	19266	38531	+19266
Sat	7.0	6.0	-1.0	67430	57797	-+9633
Sun	2.0	2.0	0.0	19266	19266	0
Weekly totals	**14.0**	**14.5**	**+0.5**	**134859**	**139676**	**+4816**

[1] Load duration change calculated as load duration in 3B minus load duration in 3A.

[2] Recharging loads calculated by dividing the recharging rate for BEV specified in Chapter 5 (2.4kWh) by 1000 so as to be in MW/h, then multiplying this by the net change in recharging load duration in hours, then by the number of vehicles to which the change applied (50% of the BEV population fall within subgroup *Ultimate*: 4,136,666 vehicles).

[3] Net change in daily recharging load calculated as daily load for 3B minus daily load for 3A.

Table 9-9: Relative differences made to recharging durations and loads by the application of load-shifting in 3A and 3B for vehicles travelling average plus SD daily mileages (subgroup *Extra*).

Day of the test week	Load duration (h)		Load duration change[1] (h)	Daily load (MWh)		Net change in load[3] (MWh)
	3A	3B		3A	3B	
Mon	0.0	2.5	+2.5	0	19266	+19266
Tue	4.0	2.5	-1.5	30825	19266	-11559
Wed	4.0	3.0	-1.0	30825	23119	-7706
Thu	4.0	3.0	-1.0	30825	23119	-7706
Fri	4.0	6.0	+2.0	30825	46237	+15412
Sat	7.0	6.0	-1.0	53944	46237	-7706
Sun	3.5	4.0	+0.5	26972	30825	+3853
Weekly totals	**26.5**	**27.0**	**+0.5**	**204215**	**208068**	**+3853**

[1] Load duration change calculated as load duration in 3B minus load duration in 3A.

[2] Recharging loads calculated by dividing the recharging rate for BEV specified in Chapter 5 (2.4kWh) by 1000 so as to be in MW/h, then multiplying this by the net change in recharging load duration in hours, then by the number of vehicles to which the change applied (40% of the BEV population fall within subgroup *Extra*: 3,210,933 vehicles).

[3] Net change in daily recharging load calculated as daily load for 3B minus daily load for 3A.

Table 9-10: Net BEV daily loads in 3A versus 3B. Load shifted provided in MWh but also as a percentage of total plug-in vehicle recharging loads per day.

Day of the test week	Net BEV load (MWh)		Total Plug-in vehicle load (MWh)		Net load shifted (h)	Percentage of total plug-in load from 2B shifted (%)
	3A	3B	3A	3B		
Mon	17339	41421	20342	44424	+24082	+118
Tue	48164	41421	51167	44424	-6743	-13
Wed	57797	50091	60799	53093	-7706	-13
Thu	67430	45274	70432	48277	-22155	-31
Fri	67430	102108	70432	105110	+34678	+49
Sat	138712	121373	141715	124376	-17339	-12
Sun	63576	67430	66579	70432	+3853	+6
Weekly totals	**460448**	**469117**	**481466**	**490135**	**+8670**	**+2**

Compared to 3A, 3B added 24,082 MWh of load to Monday, but further subtracted loads from Tuesday through Thursday (36,605 MWh). 17,339 MWh of load was removed from Saturday but 34,678 MWh was added to Friday and 3853 MWh added to Sunday.

Please note that discrepancies have been introduced in 3A and 3B, relating to the number of hours required for recharging by *Extra* subgroups (in 3A recharging half an hour less) and *Ultimate* subgroups (in 3B recharging half an hour more) versus vehicles travelling the same mileages in 2B. These discrepancies were due to rounding recharging need to the nearest half hour based on daily mileages, not the weekly total required. This in turn has made a difference to the balance sheet of subtraction and addition of loads when summed to weekly totals from Table 9-8 to Table 9-10. Total plug-in vehicle demand in 3B was 2% larger than in 3A where really there should be no net change. Details for how this came about can be found in Appendix 3, but the issue will be further discussed in the evaluation.

In Fig. 9.33 it can be seen that the difference between maximum and minimum demand under 3A conditions is identical to the difference between maximum and minimum demand under 3B conditions. There is however a decrease in the difference between maximum and minimum demand relative to that of existing demand. Fig. 9.34 shows that the narrowing of the gap between daily maxima and minima relative to that of existing demand arose in both 3A and 3B as a result of plug-in vehicle recharging raising daily minimum demand (by the same amount in both scenarios), whilst daily maximum demand was unaffected.

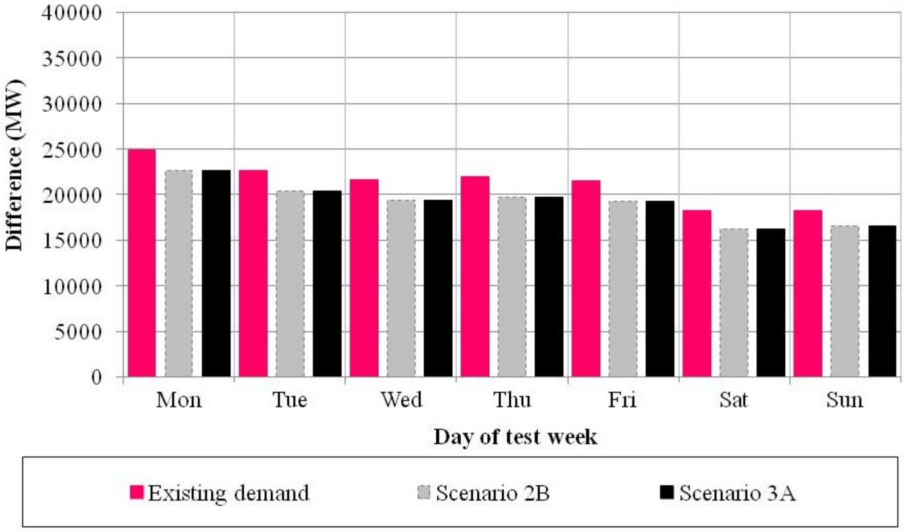


Fig. 9.33. Variability in existing demand and in demand under the conditions of scenarios 3A and 3B, as plotted by the absolute difference between daily maxima and minima.

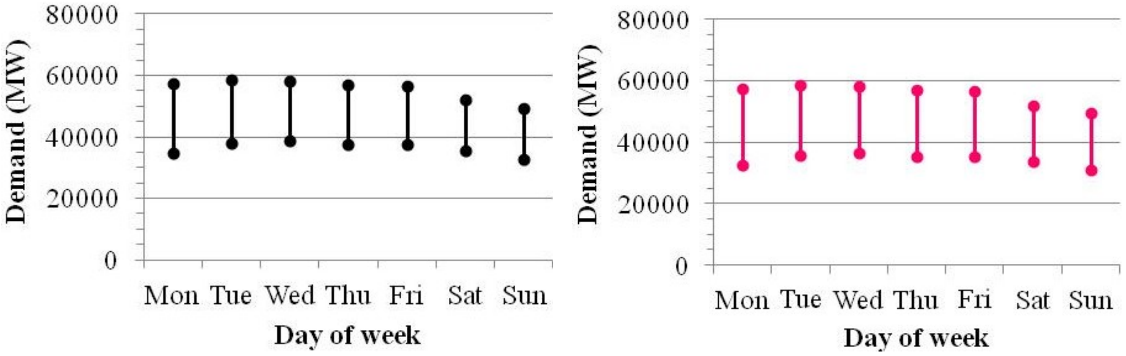


Fig. 9.34. Variability of demand under the conditions of scenario 3A and 3B (left) compared to variability of existing demand (right), as plotted by the range over which demand varied per day between demand maxima and minima.

9.2.3.3 Comparing 1B to 2B and 3B

The arbitrary network limit of 60,000 MW was breached on every day of the test week in 1B, the maximum breach being by 10,012 MW on Tuesday. In 2B or 3B breach was avoided on every day of the test week due to the restricted recharging conditions applied to both by Recharging Regimes (see Fig. 9.35). In comparing scenarios 1B, 2B and 3B it is shown how at first, the addition of recharging loads from plug-in vehicles, if the vehicles were allowed to recharge upon returning home, could have increased the highest annual demand by 11,458 MW – an increase of 20% above the existing demand peak. Then, in 2B and also applied in 3B, Recharging Regimes spread loads more evenly over individual days of the test week and as a result all network limit breaches were avoided and daily peaks remained unchanged.

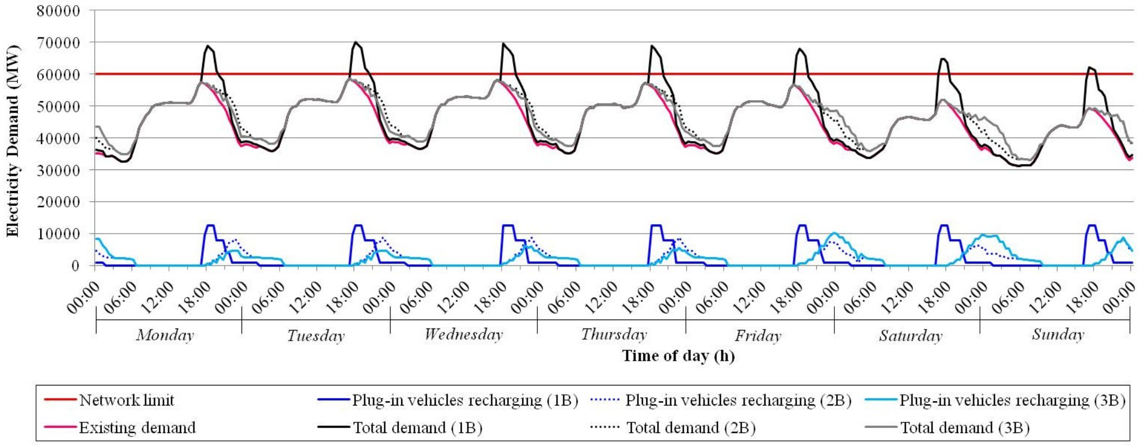


Fig. 9.35. Results comparison of 1B, 2B and 3B plotted over existing demand, showing the impact of changing assumptions about daily vehicle mileages.

Lastly, in 3B load-shifting was applied on top of Recharging Regimes to try to take advantage of lulls in existing demand over the weekend and minimise impacts on workdays when existing demand is higher. This is most visible in Fig. 9.35 on Monday night and Tuesday night where load has been shaved off and on Friday night and Saturday night where loads have been deposited.

The amount of load shifted per day of the week in 3B depended upon changing recharging load durations for vehicles in *Ultimate* and *Extra* subgroups. These changes are compared against the same vehicles under 1B and 2B conditions in Tables 9-11 and 9-12. Note that load durations and daily loads are identical between 1B and 2B. Demand curves for 1B and 2B are vastly different but the difference between them is not a result of load-shifting (as applied in 3B between different days) but a result of the presence (in 2B) or absence (in 1B) of the application of Recharging Regimes.

Table 9-11: Relative differences made to recharging durations and loads by the application of load-shifting in 3B versus 1B and 2B, for vehicles travelling average daily mileages (50% of BEV population in 1B and 2B, labelled subgroup *Ultimate* in 3B).

Day of the test week	Load duration (h)		Load duration change[1] (h)	Daily load (MWh)		Net change in load[3] (MWh)
	1B and 2B	3B		1B and 2B	3B	
Mon	2.0	0.5	-1.5	19266	4816	-14449
Tue	2.0	0.5	-1.5	19266	4816	-14449
Wed	2.0	1.0	-1.0	19266	9633	-9633
Thu	2.0	0.5	-1.5	19266	4816	-14449
Fri	2.0	4.0	+2.0	19266	38531	+19266
Sat	2.0	6.0	+4.0	19266	57797	+38531
Sun	2.0	2.0	0.0	19266	19266	0
Weekly totals	**14.0**	**14.5**	**+0.5**	**134859**	**139676**	**+4816**

[1] Load duration change calculated as load duration in 3B minus load duration in 2B or 1B (1B and 2B identical).

[2] Recharging loads calculated by dividing the recharging rate for BEV specified in Chapter 5 (2.4kWh) by 1000 so as to be in MW/h, then multiplying this by the net change in recharging load duration in hours, then by the number of vehicles to which the change applied (50% of the BEV population fall within subgroup *Ultimate*: 4,136,666 vehicles).

[3] Net change in daily recharging load calculated as daily load for 3B minus daily load for 2B or 1B (1B and 2B identical).

Table 9-12: Relative differences made to recharging durations and loads by the application of load-shifting in 3B versus 2B, for vehicles travelling average plus SD daily mileages (40% of BEV population in 1B and 2B, labelled subgroup *Extra* in 3B).

Day of the test week	Load duration (h)		Load duration change[1] (h)	Daily load (MWh)		Net change in load[3] (MWh)
	1B and 2B	3B		1B and 2B	3B	
Mon	3.5	2.5	-1.0	19266	19266	-7706
Tue	4.0	2.5	-1.5	19266	19266	-11559
Wed	4.0	3.0	-1.0	19266	23119	-7706
Thu	4.0	3.0	-1.0	19266	23119	-7706
Fri	4.0	6.0	+2.0	19266	46237	+15412
Sat	4.0	6.0	+2.0	19266	46237	+15412
Sun	3.5	4.0	+0.5	19266	30825	+3853
Weekly totals	**27.0**	**27.0**	**0.0**	**208068**	**208068**	**0**

[1] Load duration change calculated as load duration in 3B minus load duration in 1B or 2B (1B and 2B identical).

[2] Recharging loads calculated by dividing the recharging rate for BEV specified in Chapter 5 (2.4kWh) by 1000 so as to be in MW/h, then multiplying this by the net change in recharging load duration in hours, then by the number of vehicles to which the change applied (40% of the BEV population fall within subgroup *Extra*: 3,210,933 vehicles).

[3] Net change in daily recharging load calculated as daily load for 3B minus daily load for 1B or 2B (1B and 2B identical).

In Table 9-13, total daily loads for BEV and for all plug-in vehicles together are given for 1B and 2B together (identical), and for 3B for comparison. The net shifting of loads from and to different days of the week is provided in MWh and as a percentage of total plug-in vehicle loads per day of the test week. Compared to 1B and 2B, 3B subtracted 87,658 MWh of load from workdays Monday through Thursday and deposited 92,475 MWh over weekend days Friday through Sunday.

Table 9-13: Net BEV daily loads in 3B versus 1B and 2B. Load shifted provided in MWh but also as a percentage of total plug-in vehicle recharging loads per day.

Day of the test week	Net BEV load (MWh)		Total Plug-in vehicle load (MWh)		Net load shifted (h)	Percentage of total plug-in load shifted (%)
	1B and 2B	3B	1B and 2B	3B		
Mon	63576	41421	66579	44424	-22155	-33
Tue	67430	41421	70432	44424	-26009	-37
Wed	67430	50091	70432	53093	-17339	-25
Thu	67430	45274	70432	48277	-22155	-31
Fri	67430	102108	70432	105110	+34678	+49
Sat	67430	121373	70432	124376	+53944	+77
Sun	63576	67430	66579	70432	+3853	+6
Weekly totals	**464301**	**469117**	**485319**	**490135**	**+4816**	**+1**

Please note that a discrepancy was introduced in 3B relating to the number of hours required for recharging by *Ultimate* subgroups (recharging half an hour more) versus vehicles travelling the same mileages in 2B. These discrepancies were due to the rounding of recharging need to the nearest half hour based on daily mileages, not the weekly total required. This in turn has made a difference to the balance sheet of subtraction and addition of loads when summed to weekly totals in Table 9-11 and Table 9-13. Total plug-in vehicle demand in 3B was 1% larger than in 1B and 2B. Details for how this came about can be found in Appendix 3, but the issue will be further discussed in the evaluation.

In Fig. 9.36 it can be seen that the difference between maximum and minimum demand increases under 1B conditions but decreases under 2B and 3B conditions, relative to existing demand. The decrease in difference between maximum and minimum demand under 3B conditions is identical to that under 2B conditions.

Fig. 9.37 shows that the widening of the gap between daily maxima and minima relative to that of existing demand arose in 1B was a result of plug-in vehicle recharging raising daily maximum demand, whilst daily minimum demand was unaffected. Fig. 9.38 shows that the narrowing of the gap between daily maxima and minima relative to that of existing demand arose in both 2B and 3B as a result of plug-in vehicle recharging raising daily minimum demand (by the same amount in both 2B and 3B), whilst daily maximum demand was unaffected.

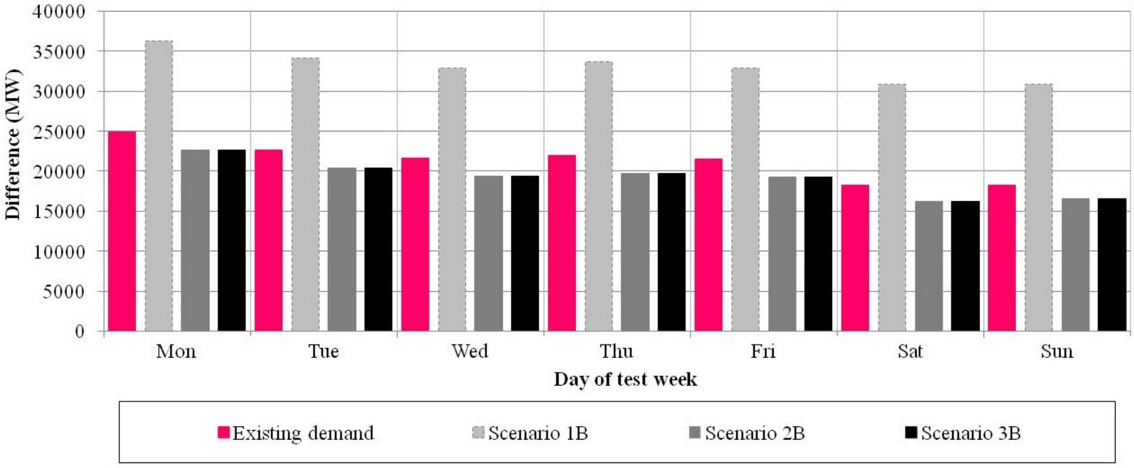


Fig. 9.36. Variability in existing demand versus variability in demand under the conditions of scenarios 1B, 2B and 3B, as plotted by the absolute difference between daily maxima and minima.

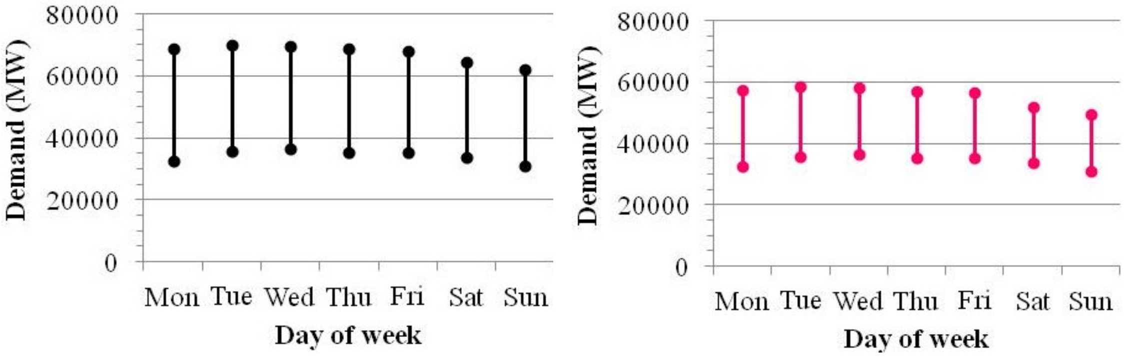


Fig. 9.37. Variability of demand under the conditions of scenario 1B (left) compared to variability of existing demand (right), as plotted by the range over which demand varied per day between demand maxima and minima.

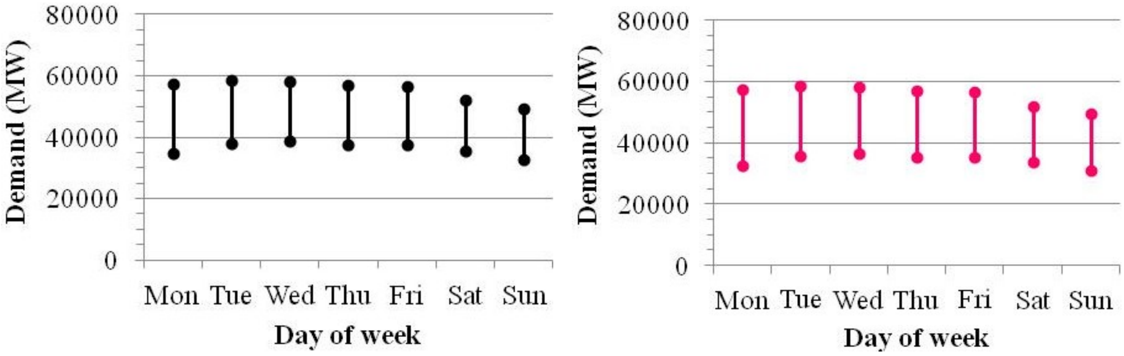


Fig. 9.38. Variability of demand under the conditions of 2B and 3B (left) compared to variability of existing demand (right), as plotted by the range over which demand varied per day between demand maxima and minima.

9.3 DISCUSSION OF IMPACTS ARISING FROM THE APPLICATION OF SCENARIOS

In this part of Chapter 9 the impact upon national electricity demand of adding of plug-in vehicle recharging loads according to the scenarios tested in this study are analysed in terms of how they affect the magnitude, duration and timing of peaks and lulls and how they influence the overall shape of total demand.

9.3.1 MAGNITUDE IMPACTS

As shown in Table 9-1 and Fig. 9.21, unrestricted recharging (scenario 1) breached the network limit on every day of the study week, regardless of whether vehicles were assumed to require a flat-to-full recharge in 1A, or a more realistic mileage-based recharging requirement in 1B.

According to Table 9-1, the smallest breach of the arbitrary network limit of 60,000 MW was by 2066 MW, occurring on Sunday and the largest breach was by 10,012 MW, occurring on Tuesday – the day of highest demand in the test week and the highest annual demand for the test year of 2009 [8]. This constituted a 20% increase above the highest peak in existing demand for the year 2009 from 58,554 MW to 70,012 MW. It would have constituted a 19% increase in demand above the highest demand ever met for Great Britain, as noted in Chapter 7, from 59,880 MW [8] to 71,338 MW.

Daily minima were not affected by conditions applied in 1A or 1B, but both equally increased the magnitude of peaks – see Fig. 9.23. According to Table 9-2, daily demand peaks increased by between 11,247 MW and 11,628 MW for Monday to Friday – an increase of 19-20% relative to peak demand on those days. On Saturday and Sunday, peak demand increased by 12,636 MW, constituting a 24% increase in peak demand on Saturday and 26% on Sunday.

When Recharging Regimes were applied (introduced in scenario 2, applied again in scenario 3 together with load-shifting between days of the week), breaches of the arbitrary network limit of 60,000 MW were completely avoided – see Fig. 9.24 and Fig. 9.32. Breaches were avoided regardless of differences in assumed daily vehicle energy usage in 2A versus 2B. In fact the magnitude of daily maximum (peak) demand in 2A, 2B, 3A and 3B was solely attributed to that of existing demand and was not influenced by recharging loads, unlike under 1A and 1B conditions – compare Fig. 9.21 to Fig. 9.24 and Fig. 9.32.

The application of Recharging Regimes did, however, affect the magnitude of daily demand minima. Daily demand minima in scenario 2 were increased by differing amounts depending upon assumptions made about daily mileages of BEV. According to Table 9-3, under 2A conditions where flat-to-full recharging for all vehicles was assumed, synonymous with vehicles having travelled their maximum mileage every day: daily minima increases were smaller on weekends than on workdays. Minimum demand under 2A conditions increased by 4925 MW (23%) on Sunday and 7683 MW (16%) on Saturday, but by between 9390 MW (26%) and 9520 MW (29%) on workdays.

According to Table 9-3, under 2B conditions where the BEV population was assumed to have vehicles travelling different mileages, requiring different recharging durations to fully recover their battery SOC: the percentage increase for daily minima above that of existing demand on every day of the week was much smaller on every day compared to the difference under 2A conditions. The pattern of demand minima being increased more on workdays compared to weekends was present but less pronounced: minima increased by 1766 MW on Sunday and by 2060 MW on Saturday, but by between 2242 MW and 2272 MW on workdays. Percentage increase in daily demand minima was around 6% to 7% on every day.

Under scenario 3 conditions (both 3A and 3B), daily minimum demand increased (and daily maximum demand did not) by amounts identical to those under 2B conditions. In other words: load-shifting applied exclusively in scenario 3 had no effect on daily demand maxima or minima. Maxima were unaffected because no alterations were made to the number of vehicles present in recharging groups set by the implementation of Recharging Regimes. Minima were unaffected by load-shifting, because even though demand was shifted between days and load durations extended for vehicles on days receiving additional loads, the extended load durations were insufficient to cause overlap with any demand minima on those days.

9.3.2 DURATION IMPACTS

In this study, recharging load durations are influenced by two factors: assumptions made about daily mileages travelled as an indicator for vehicle daily energy usage and timing (which will be discussed in the next section). In this study 'how much energy a vehicle is required to recharge' is assumed not to affect the rate at which charge is drawn, but only affect the length of time for which the vehicle must recharge.

In scenario 1, assumptions made about daily mileages influence the length of 'at risk' periods where the network limit is breached – see Table 9-1 for details. Breaches of the network limit lasted around an hour longer for flat-to-full recharging on workdays in 1A than in 1B (see Fig. 9.21).

In scenario 2 there are no network limit breaches, but the effects of making different assumptions about daily vehicle energy usage instead affect the duration of peaking periods of total demand. When vehicle energy usage in 2A is maximised by assuming all vehicles require flat-to-full recharging, the duration of peaking periods is more extended (overall shape of load is wider) than when more realistic daily mileages are adopted for the population in 2B (see Fig. 9.24).

Results for 3A and 3B are similar to 2B (see Fig. 9.29 and Fig. 9.32) because both variations assume the same vehicle energy usage and use Recharging Regimes that split vehicles up into the same number of groups as in scenario 2, following the same recharge start times for days when vehicles are recharging. In 2B, 3A and 3B, only the 10% of vehicles specified as travelling maximum mileages are influencing the magnitude of daily minima. As the number of vehicles – 10% of BEV – is the same in these three variations and load-shifting applied in 3A and 3B increase recharging load durations receiving days but not enough to influence their demand minima, the impact upon the magnitude of daily minima is identical across 2B, 3A and 3B.

The subtle differences between 3A and 3B with regards to the duration of peaking periods in total demand and between these and 2B arise from the shifting of the duration of loads from workday evenings to weekend evenings – see Table 9-7 and Table 9-10. Under 3A conditions, the impact of recharging on peak load duration on Monday, Tuesday and Wednesday is lessened, but increases peak load durations on Saturday when compared to total load from 2B – see Fig. 9.29. So the widening of peak period durations for Monday to Wednesday is less in 3A than in 2B, meanwhile the peak period duration of Saturday is extended and more comparable to the load seen for the same day in 2A which assumed flat-to-full recharging for all vehicles.

9.3.3 IMPACTS UPON TIMING

In scenario 1 both variations add to peak demand, but also change the timing of daily peaks on workdays (see Table 9-2). Weekend peak times are unchanged by either variation, but both variations push the timing of daily peaks later by 1 h from Monday to Friday. Scenario 2 and 3 variations by comparison do not alter the timing of peak demand on any day.

It is the timing of recharging loads in scenario 1 versus scenarios 2 and 3, that determines the noted difference where in scenario 1, recharging added to the magnitude of daily demand maxima without influencing daily demand minima, but in scenarios 2 and 3 exhibit the opposite characteristics: they increased the magnitude of daily demand minima but not daily demand maxima. In scenario 1 all vehicles were timed to recharge simultaneously, whilst in Scenarios 2 and 3 this was prevented, thus avoiding any increase in daily maxima.

9.3.4 IMPACTS UPON OVERALL SHAPE OF DEMAND PROFILES

In scenario 1, unrestricted recharging makes the overall total load profile more peaky – compare 1A (Fig. 9.3) and 1B (Fig. 9.4) to existing demand (Fig. 9.1). This evidenced by the increased difference between daily maxima and minima – see Fig. 9.22. In scenario 1 neither variation affected daily minima but both added to the magnitude of daily demand maxima (peaks) – see Fig. 9.23.

The increase in difference between daily demand maxima and minima was strongest for weekends. The difference on Saturday and Sunday is 69% larger than it was before the addition of plug-in vehicle recharging loads (see Table 9-2). In comparison for workdays – Monday to Friday – the difference is amplified by 46% to 53%. These impacts are the same for both 1A and 1B.

Note also the impact of changing assumptions about vehicle daily recharging needs based on daily mileages. In 1B this leads to a sharper peak than if unrealistic flat-to-full recharging for all vehicles is assumed as in 1A – see Fig. 9.21.

In contrast the application of Recharging Regimes in scenario 2 does not exacerbate peaks and has a smoothing effect – compare Fig. 9.6 and Fig. 9.7 to existing demand prior to the addition of recharging loads in Fig. 9.1. The smoothing effect can be considered in terms of the changing difference between daily maxima and minima – see Fig. 9.25. The smoothing effect reducing the difference between daily minima and maxima differs depending upon the assumptions made about vehicle daily energy usage. Flat-to-full recharging has a stronger levelling effect in 2A, reducing the difference by 27% to 44% over the week. Loads resulting from more realistic mileage assumptions used in 2B reduce the difference between daily minima and maxima by between 9% to 11%, therefore reducing it by 18% to 33% less than in 2A.

Scenario 3 results are comparable to scenario 2, specifically 2B with which they share conditions for assumed distribution of daily mileages travelled across the BEV population. both 3A and 3B like 2B, avoid making demand more peaky by avoiding increasing daily demand maxima (compare Fig. 9.10 and Fig. 9.11 to Fig. 9.1) whilst also levelling demand. The difference between daily demand maxima and minima is decreased (see Fig. 9.33) and this comes from affecting daily demand minima (see Fig. 9.34).

9.4 SUMMARY OF FINDINGS

Unrestricted recharging in scenario 1 substantially increased existing peaks in demand above the arbitrary network limit of 60,000 MW to more than 70,000 MW (an increase of more than 19% above the highest demand ever met). Changing assumptions about vehicle energy usage patterns across the BEV population shortened the ‘at-risk’ period where demand breached the arbitrary limit of 60,000 MW from a total of 24.5 h in 1A to 15 h in 1B but made total demand profiles more peaky in shape.

Unrestricted recharging also increased the variability of demand by 46% to 70% based on the test week. This impact ignored assumptions relating to individual vehicle daily energy usage, because changes to daily vehicle energy usage in this study affect duration of recharging per vehicle only, not the rate at which those vehicles draw charge from the network to replenish their batteries SOC.

Recharging Regimes in scenarios 2 and 3 prevented recharging loads from adding to existing demand in any way that would cause breach of the arbitrary network limit of 60,000 MW and instead allow plug-in vehicle recharging to level total demand, reducing the difference between daily demand maxima and minima. Changing assumptions about vehicle daily energy usage affected the strength of the levelling effect which was at its strongest when flat-to-full recharging of all vehicles was assumed in 2A.

Where travel behaviour patterns in daily vehicle energy usage allowed for partial recharging, load-shifting in 3A was able to shift 75,136 MWh in 3A and 86,758 MWh in 3B of recharging load from workdays to weekends where existing demand is lower. Accounting for discrepancies in recharging durations in 3A and 3B compared to vehicles travelling the same daily mileages in

1B and 2B, 25,045 MWh more load was transferred from workdays to weekend days in 3B compared to 3A. This however had a far lesser impact upon total demand profiles than the implementation of Recharging Regimes.

CHAPTER 10: CONCLUSIONS AND CONTRIBUTIONS TO FIELD OF STUDY

In accordance with the main aim of the study, a tool has been created for parties interested in maintaining the national electricity supply network and parties interested in informing policy on plug-in vehicle adoption schemes and recharging behaviour control: The Parry Tool. Through choice of software employed and relatively simplistic methods presented, it is hoped that the tool will be easily modifiable by, and widely accessible to, a larger, specialist and multidisciplinary, academic and non-academic audience.

The Parry Tool enables the user to incorporate present limits to plug-in vehicle recharging demand scheduling as imposed by the state of present technology (no third party mechanism for monitoring and control of recharging), present human travel behaviour needs and existing patterns in electricity usage; into the investigation of the impacts of recharging demand impacts and the design of mitigation measures for deflecting (parrying) worst case scenarios.

Potential applications of the Parry Tool were then demonstrated (second aim of the project). The multidisciplinary/interdisciplinary information gathered by the Parry Tool was used to first to produce national demand profiles for plug-in vehicle recharging demand, calculated using socioeconomic and travel behaviour-estimated population sizes for plug-in eligible vehicles and vehicle usage patterns, which were then added to existing national electricity demand for a chosen test week – this was the first scenario subsequently tested. The information gathered by the Parry Tool was then used to inform the design of two demand management methods for plug-in vehicle recharging: Recharging Regimes and weekly recharging load-shifting – these were the second and third scenarios subsequently tested.

In this chapter, conclusions from the various quantitative and qualitative analyses drawn together by the Parry Tool are presented as answers to the primary and secondary research questions. Contributions of the study to the field of research with be summarised last. Evaluation of the project work and recommended further work will be discussed in a dedicated chapter afterwards.

10.1 ANSWERS TO PRIMARY RESEARCH QUESTIONS (PRQ)

There were five primary research questions highlighted in Chapter 1. Answers to the first three (concerning estimates for plug-in vehicle population size and travel behaviour and patterns in existing electricity demand) came initially from the collection of information and statistics by the Parry Tool through its integrated methods and analyses, but were supported later by scenario results for testing the applications of the Parry Tool. Answers to the last two (concerning the potential impact of plug-in vehicle recharging and the design of methods to schedule their demand to complement patterns in existing demand) came from the application of the Parry Tool through scenario construction and scenario results analysis. A summary of the scenarios constructed and differences in their design is summarised by Fig. 10.1.

10.1.1 HOW MANY UK VEHICLES MIGHT BE SUBSTITUTED WITH PLUG-IN VERSIONS? (PRQ:1)

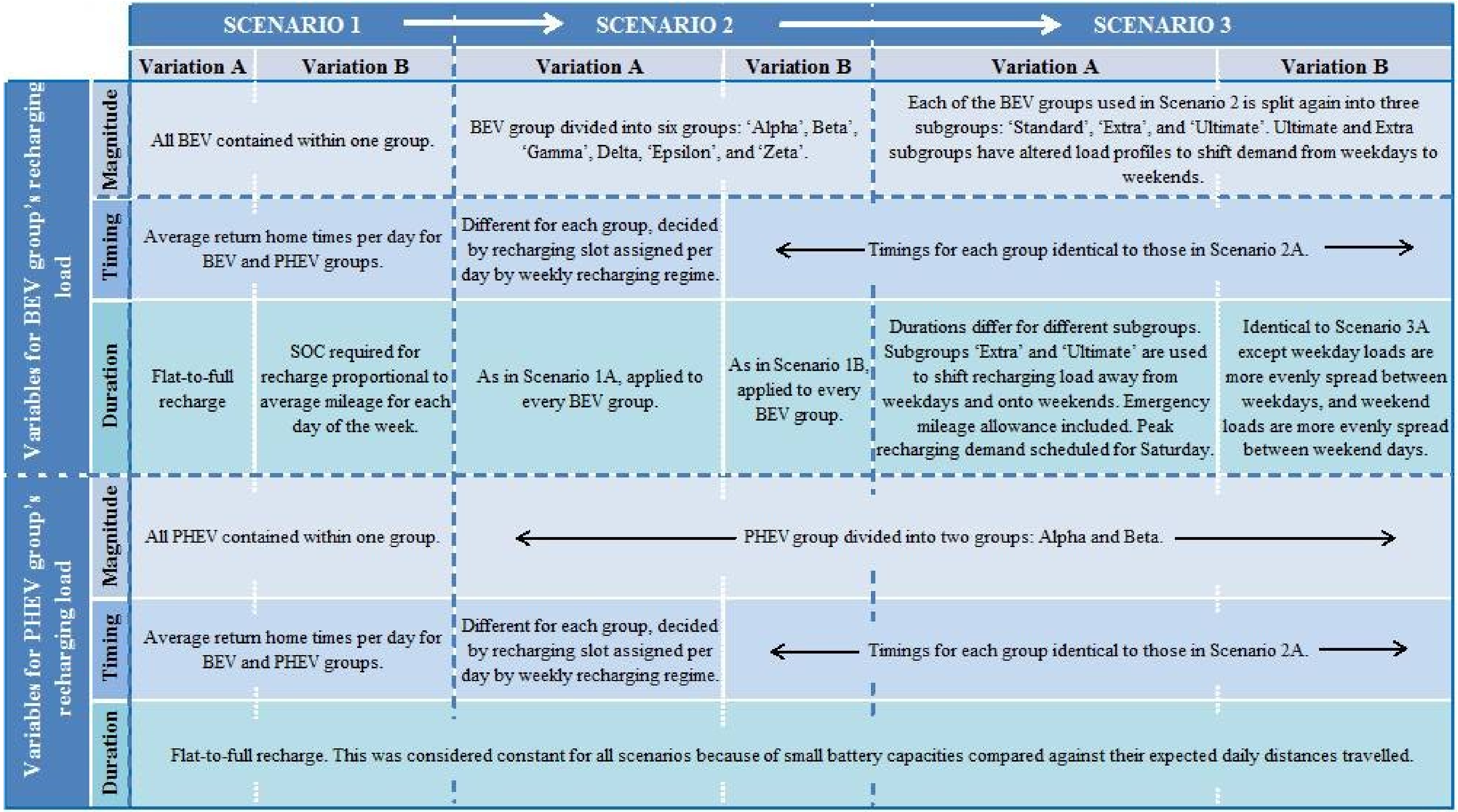
The average price of a BEV after the full plug-in car grant was applied as found by the review of information available from vehicle manufacturers was £19,876. The average maximum mileage range for BEV in March 2012 was 100.6 miles. For PHEV prices were unavailable until much later, so at the time figures were needed it was assumed they would cost at least as much or more than a BEV. The maximum range of a PHEV used to determine ownership was arbitrarily set to 500 miles, after consideration of vehicle fuelled and electric ranges and the need to recharge (and to have government recommended driving breaks).

It was assumed therefore in NTS statistics extraction method that no household with an income of under £35k/a could afford a plug-in vehicle. After this assumption was made, household four-wheeled vehicles listed in the NTS were considered for feasibility of plug-in vehicle replacement. Vehicles travelling over 500 miles were assumed ineligible for plug-in replacement. Vehicles that travelled more than 100.6 miles in one day of the travel week - but no more than 500 miles during any day of the travel week – were considered eligible for replacement with a PHEV. Vehicles travelling 100.6 miles or less on every single day of the travel week were considered eligible for replacement with a BEV.

35% of private cars registered as ‘Private and light goods (PLG)’ were assumed to be owned by households earning at or above the required threshold of £35k/a. After scaling up to national estimates from the proportions of BEV, PHEV and vehicles ineligible for replacement with either within that income-specified population estimate:

- 8,027,332 (84.20%) were BEV
- 1,501,290 (15.75%) were PHEV
- Leaving 5375 (0.06%) vehicles neither replaced with a BEV or PHEV

In total it was estimated that 9,528,622 vehicles could be eligible for replacement with a plug-in vehicle.



		SCENARIO 1 →		SCENARIO 2 →		SCENARIO 3	
		Variation A	Variation B	Variation A	Variation B	Variation A	Variation B
Variables for BEV group's recharging load	Magnitude	All BEV contained within one group.		BEV group divided into six groups: 'Alpha', Beta', 'Gamma', Delta, 'Epsilon', and 'Zeta'.		Each of the BEV groups used in Scenario 2 is split again into three subgroups: 'Standard', 'Extra', and 'Ultimate'. Ultimate and Extra subgroups have altered load profiles to shift demand from weekdays to weekends.	
	Timing	Average return home times per day for BEV and PHEV groups.		Different for each group, decided by recharging slot assigned per day by weekly recharging regime.	← Timings for each group identical to those in Scenario 2A. →		
	Duration	Flat-to-full recharge	SOC required for recharge proportional to average mileage for each day of the week.	As in Scenario 1A, applied to every BEV group.	As in Scenario 1B, applied to every BEV group.	Durations differ for different subgroups. Subgroups 'Extra' and 'Ultimate' are used to shift recharging load away from weekdays and onto weekends. Emergency mileage allowance included. Peak recharging demand scheduled for Saturday.	Identical to Scenario 3A except weekday loads are more evenly spread between weekdays, and weekend loads are more evenly spread between weekend days.
Variables for PHEV group's recharging load	Magnitude	All PHEV contained within one group.		← PHEV group divided into two groups: Alpha and Beta. →			
	Timing	Average return home times per day for BEV and PHEV groups.		Different for each group, decided by recharging slot assigned per day by weekly recharging regime.	← Timings for each group identical to those in Scenario 2A. →		
	Duration	Flat-to-full recharge. This was considered constant for all scenarios because of small battery capacities compared against their expected daily distances travelled.					

Fig. 10.1. Summary of project scenarios and the variables kept static or changed for each.

10.1.2 WHEN WOULD IT BE BEST TO SCHEDULE NEW LOADS FROM PLUG-IN VEHICLE RECHARGING? (PRQ:2)

Analysis of half-hourly national electricity demand data from National Grid plc [8] over 8 years showed that the highest peak demand met to date by the UK electricity supply system was 59,880 MW. There were diurnal, weekly and seasonal patterns in demand:

- Peaks occurred diurnally (every evening), indicating the daily cycle of demand.
- Diurnal maxima (peaks) and minima were highest on workdays and lowest on weekend days, highlighting a weekly cycle of demand.
- Summer months had daily and weekly maxima (peaks) that were lower than those in winter months. Daily and weekly demand minima were less influenced by seasons than maxima but similarly were highest in winter months and lowest in summer months. This evidenced the seasonal cycle of demand.

Lulls (minima) in demand – of interest for demand levelling purposes – were therefore noted to occur nightly in the early hours of the morning, weekly (specifically on weekends) and seasonally specifically over summer months. Daily and weekly demand patterns in the timing, duration and magnitude of existing loads were considered to be the better prospect for load levelling because the seasonal cycle was deemed unsuitable in light of plug-in vehicle specifications reviewed from manufacturers and vehicle travel behaviour analysis of the National Travel Survey [1]. These then constituted the timings for when best to add new loads to existing electricity demand, indicating that plug-in vehicle recharging profiles should ideally follow both a daily and a weekly regime.

The timing of the highest demand of every year was noted to fall consistently between 17:00 h and 17:30 h, on a workday evening – usually on a Tuesday or Thursday. No annual peak over the years 2002-2011 occurred on a Friday, Saturday or Sunday. So, avoiding peak times on workdays was assumed a priority and it was deemed that any test week used for impact assessment should include the day of highest annual demand.

Preliminary theoretical testing showed that there are significant at risk periods associated with prospect of simultaneous recharging of plug-in vehicles, particularly concerning coincidence of BEV recharging, and BEV together with PHEV recharging, based on population estimates in this study. So the question of "when" might better be adjusted to reflect this by correcting the question to be "when, for whom?" with regards to recharging scheduling. In other words: splitting plug-in vehicle populations into groups that start recharging at different times.

When estimates for plug-in vehicle populations were used to construct recharging load profiles in the first application of the Parry Tool for Scenario 1, results illustrated the potentially damaging impact of plug-in vehicles recharging simultaneously upon arrival home. Daily peaks were sharper and far greater in magnitude than the existing electricity generation and supply system has ever had to face before – up to 19% higher (70,012 MW over a half hour period) than the highest demand ever met (59,880 MW over a half hour period in the year 2007).

10.1.3 WHAT ARE THE TRAVEL BEHAVIOUR PATTERNS OF VEHICLES THAT MIGHT BE SUBSTITUTED WITH PLUG-IN VERSIONS? (PRQ:3)

Vehicles that were deemed replaceable with BEV and PHEV in the NTS [1] from the NTS statistics extraction method (Part 1) presented in this study, travel behaviour was investigated to determine daily mileage on each day of the working week and average departure from and return to home times. Average daily mileages were between 20.7 and 22.9 miles for BEV, with little apparent difference between workdays and weekends. This implied an average daily energy usage of 4.5kWh to 5.0 kWh. Workday usage varied from 4.8 to 5.0 kWh Monday through to Friday, whilst Saturday and Sunday averaged 4.7 kWh and 4.5 kWh respectively.

Average daily mileages for PHEV were longer than for BEV, between 65.6 and 69.8 miles Monday to Thursday, then slightly higher from 73.4 to 69.0 miles from Friday to Sunday. This implied average daily energy usage that surpassed the PHEV battery capacity (16 kWh, equivalent to 50 miles) on every day of the week.

Average daily departure from home times were between 09:25 h and 09:38 h on workdays, markedly later on Saturday and Sunday – 11:10 h and 11:43 h – for BEV. PHEV departure from home times were typically a little earlier on every day of the week. Average daily departure times were between 09:13 h and 09:31 h on workdays, markedly later on Saturday and Sunday – 10:56 h and 11:34 h – for PHEV.

Average daily return home times were between 17:19 h and 17:38 h on workday and slightly earlier on weekends – 16:20 h and 16:17 h for Saturday and Sunday – for BEV. PHEV were generally later returning home on every day. Average daily return home times were between 17:42 h and 18:02 h on workday and slightly earlier on weekends – 16:59 h and 16:58 h for Saturday and Sunday – for PHEV.

In other words, if the inclination to recharge upon arrival home was a presiding default determinant of recharging start time, return home times would mean coincidence of recharging with existing demand peaks for both PHEV and BEV. If recharging is restricted too at-home-only as it is in this study, then recharging windows for both BEV and PHEV are more restricted on workdays than on weekends, with BEV recharging windows consistently larger than those for PHEV on every day. PHEV have recharging windows of 15.0 h to 15.5 h from Monday to Thursday, 16.0 h to 16.3 h from Friday to Sunday. BEV have recharging windows of 15.5 h to 16.0 h from Monday to Thursday, 17.0 h to 19.0 h from Friday to Sunday.

Further analysis (scatter graphs, SD for averages taken) showed that there could be a great deal of variation either side of these averages, for both PHEV and BEV. This was especially noticeably on weekends when, presumably without the interference of work patterns, driving patterns were subject to personal interests and capacity for travel. The simple averages collected seemed to partially reflect this, leading to recharging windows on weekends being larger than those for workdays.

The broader pattern that departures take place towards the start of the day and returns towards the end of the day was still noticeable in the scatter graphs. What was also noticeable was the tendency for there to be significantly less travel over the early hours of the morning, presumed to be predominantly coincident with human sleeping patterns – an ideal time for recharging to be scheduled from the perspective of vehicle users. Judging from the scatter graphs, there seemed also to be a sharper rise in departures, whereas returns increased more gradually as the day progressed and also seemed to have a more gradual decline, except on weekends where departure and returns seemed to be have more gradual increase and decrease in the number occurring.

10.1.4 HOW MIGHT THE ADDITION OF RECHARGING LOADS FROM PLUG-IN VEHICLES ALTER THE MAGNITUDE, TIMING, DURATION AND SHAPE OF TOTAL NATIONAL DEMAND? (PRQ:4)

Information and statistics gathered together by the Parry Tool were used to construct Scenario 1 to answer this question. The analysis of scenario 1 showed that plug-in vehicle recharging as modelled in this study could significantly affect the magnitude of daily demand peaks if unrestricted charging were allowed. The timing of peak demand was pushed later by an hour and became dependent upon the timing of simultaneity when all PHEV and all BEV are assumed to be recharging simultaneously.

Changing assumptions about vehicle energy usage did not decrease the magnitude of the resulting peaks, but it did sharpen them. Results analysis suggested that unrestricted recharging could also increase the difference between daily minima and maxima by between 46 and 69%. The duration of at-risk periods where electricity demand would breach the 60,000 MW network limit imposed by this study was reduced when more realistic energy usage patterns through the introduction of limited mileage variation, but this also made the shape of the demand curve have sharper peaks on each day.

The biggest impact of unrestricted recharging was upon peak magnitude, increasing it by 10032 MW (19%) above the highest demand the UK electricity supply system has ever met, which could in turn require supply and network capacity reinforcement. This plus the likelihood of sharper peaks within the total demand shape could introduce challenges for regulation and increase the need for fast-dispatch generators – which are typically fossil fuelled (natural gas) – to compensate. Increasing the degree of oscillation between maximum and minimum demand will also require generation to vary output accordingly, leading generators to operate at optimum efficiency for shorter periods of time, presumably adding to their wear and tear.

10.1.5 HOW MIGHT ELECTRICITY DEMAND FROM PLUG-IN VEHICLE RECHARGING BE SCHEDULED TO COMPLIMENT PATTERNS IN EXISTING DEMAND? (PRQ:5)

A design strategy was produced to apply the information and statistics gathered by the Parry Tool to the construction of a recharging scheduling method that utilised compatible patterns in existing electricity demand. Recharging window sizes, flat-to-full recharging times, the relative size of recharging demand as a result of simultaneity for PHEV versus BEV and present technology were used to scope the prospects for how best to schedule demand from the two different vehicles considered in this study.

It was also found that the majority of plug-in vehicle manufacturers either had installed, or planned to install into their vehicles: mechanisms that would allow recharging to be set on a timer and/or activated remotely, opening up the possibility for scheduling recharging demands. Unfortunately the majority of research that handles plug-in vehicle recharging scheduling, assumes either very basic one-slot scheduling, recharging upon arrival home, or (as in most research) assume without question, the existence a third party recharging monitoring and control system. In this study, it was decided to omit that assumption and come up with an alternative, time-block method that plug-in vehicle drivers might be expected to implement using the technology presently available.

Recharging Regimes were designed that staggered recharging demand overnight by splitting vehicles into groups that began recharging at different times, tailoring timings over a week, to produce a demand curve more favourable to network operators. This was based first on the day of highest annual demand for 2009, then adjusted over the test week which included that day. This constituted the construction of Scenario 2.

Scenario 2 was directly comparable to scenario 1 and the comparison of the two shows the importance (and benefits) of scheduling recharging demand to avoid simultaneity. Benefits included complete avoidance of any breach of the imposed network limit of 60,000 MW and load-levelling.

In scenario 3 Recharging Regimes were embellished with load-shifting for recharging from workdays to weekends to further complement the weekly pattern identified in existing national electricity demand. This completed the demonstration for applications of the Parry Tool, having produced scheduled recharging that is compatible with the present state of technology, avoiding the public concerns identified for third party access and interference in personal affairs and matching human travel behaviour to established patterns in existing electricity demand.

10.1.6 COMBINED CONCLUSIONS OF SCENARIO ANALYSIS

Simultaneity of recharging loads from the number of plug-in vehicles estimated in this study could present a severe challenge to the electricity generation and supply system by producing a recharging-dependent new diurnal peak, and a sharp rise and fall in peak demand as a result. In reality it is unlikely that every plug-in vehicle would return home and be set to recharge in the same half hour, but the duration of recharging – especially for BEV – means that even coincidence over a period of several hours, around the existing peak, would lead to that simultaneity across the plug-in vehicle population. This is a greater risk because of the coincidence of return-home times and timing existing diurnal peak demand.

By far the best outcome of any of the scenarios tested was when the Parry Tool was used to inform the design of recharging scheduling. The introduction of the Recharging Regimes that split vehicles into groups scheduled to begin recharging at different times (thus avoiding simultaneity of recharging of all plug-in vehicles), prevented any breach of the imposed network limit of 60,000 MW from occurring. The Recharging Regimes also appeared versatile in that once they are set according to the worst case scenario (flat-to-full recharging), reduction in assumed vehicle energy usage does not appear to have any negative consequences barring one: lessening the potential valley-filling/load-levelling effect that the Recharging Regimes can achieve.

Where there is a loss of valley-filling potential related to lesser daily vehicle energy usage, there, however, is introduced the potential for workday-to-weekend load-shifting within the BEV population. This door swings both ways. There are limits to the workday-to-weekend load-shifting explored in Scenario 3, in that it is only viable so long as there are BEV that are not using their full potential mileage, i.e. not fully depleting their batteries on every day of the week. The effectiveness or usefulness of workday-to-weekend load-shifting would in reality depend on the proportion of BEV using smaller proportions of their battery capacities.

Considering the variability noted in this study, and the changeability of human behaviour over time, there will likely continue to be opportunities for workday-to-weekend load-shifting allowed by partial recharging, but the overall potential for it could change over time with changing travel habits. If BEV owners seek to maximise the use of their vehicles they might, for example, seek to maximise the number of miles they use those vehicles for over a given day within the bounds of convenient recharging. This would imply a greater proportion of batteries SOC would need to be preserved for daily use, leaving less leeway for partial recharging and therefore load-shifting.

Workday-to-weekend load-shifting relative to the introduction of Recharging Regimes alone as a tool for demand side management for plug-in vehicle recharging could increase or decrease proportional to vehicle energy usage. This, however, could allow the two ideas to work in concert with one another. The less vehicles utilise the full capacities of their batteries: the greater the potential for workday-to-weekend load-shifting and the greater the capacity of workday-to-weekend load levelling. The more vehicles utilise the full capacities of their batteries: the greater the day-to-day load levelling effect of Recharging Regimes.

10.2 ANSWERS TO SECONDARY RESEARCH QUESTIONS (SRQ)

The Parry Tool also laid out preliminary work to justify interest in converting road transport from dependency upon petroleum products to dependency upon electricity. This required the review of energy use in the UK to provide a philosophical and multidisciplinary:

i. List of reasons for why non-energy use of fossil fuels must be prioritised and fossil fuels – especially petroleum products – conserved for this purpose
ii. Discussion of alternative energy pathways (the path travelled by energy from sources to end use) to highlight problems concerning conflicts of interest, the effective use of resources and reducing negative impacts when making changes to energy pathways
iii. Brief analysis of UK energy use in order to rank top energy use/user groups, followed by reasoned discussion for why road transport constitutes a primary target for change
iv. Simple well-to-wheel analysis comparing petroleum products and electricity energy pathways for road transport on a novel basis (fossil fuel dependency)

The above list constitutes the secondary research questions.

A review of the importance of fossil fuels – arguably the primary energy pathway in use today – in the context of energy/non-energy use as well as the local and global detrimental impacts associated with both, started the project off from an unusual viewpoint: that reduction of fossil fuel use should be a higher priority (particularly for the UK) than mitigating emissions – problematic symptoms of fossil fuel use. The capture, storage or otherwise mitigation and reduced production are the normal focus of most studies involving energy, but for this project a broad argument for the reduction of fossil fuels was framed by the literature reviewed:

1) Non-energy use of fossil fuels – particularly Petroleum products – underpins modern civilisation and must be conserved for this purpose.
2) UK native production of fossil fuels – specifically oil and gas – is expected to decline leading to increased dependency on imports.
3) Fossil fuel imports cross many borders, making them vulnerable to stoppages by accident or incident.
4) Fossil fuel imports mostly come from increasingly politically unstable areas of the world.
5) Rate of use far exceeds rate of natural production for fossil fuels, meaning there is a threat of lock-in to an alternative energy technology that is ecologically hazardous or economically unviable as resources dwindle.
6) Similarly there is a threat of social crisis resulting from the incompatibility of present social institutions and a new energy technology, so time to match the two must be preserved, meaning fossil fuels must be rationed to buy time.
7) Relating again to the imbalance of rate of use to rate of replenishment, there is a threat of rent-seeking oil wars to control dwindling petroleum reserves (these are the most important fossil fuels, see reason 1.
8) The UK government has agreed to set targets for cutting its GHG emissions – primarily attributed to fossil fuel use in the UK – and due to having a nationalised health service is particularly concerned with air quality health impacts, caused in particular by the energy use of fossil fuels.

A brief overview of alternative energy pathways highlighted conflicts of interest and problems with ensuring the effective use of resources, particularly for the main alternatives open to road transport: Hydrogen, biofuel and electricity. Conflicts of interest were particularly apparent for Hydrogen where the parties most interested in developing Hydrogen-based transport fuels are those commercial entities who already produce Hydrogen for agricultural and other purposes, from fossil fuels – specifically: petroleum products.

Consideration of the effective use of resources highlighted that biofuel crops natively grown in the UK that complement native ecosystems in the UK are better suited for heat and power purposes, whilst non-native biofuel production, especially in the case of transport fuels, has questionable environmental impacts abroad. Consideration of negative impacts highlighted the role of combustion-based transport and the preference to avoid this type of technology and its unwanted emissions, including Hydrogen and biofuel as well as fossil fuels. Electricity and Hydrogen fuel cells are thus the better alternatives to fossil fuel, although Hydrogen is not yet derived from renewable sources, whilst its delivery system may need to be built from scratch or involve an overhaul of the existing national gas supply system.

Electricity, on the other hand was considered to provide immediate benefits through being clean at point of use, whilst it also offers excellent opportunities for transition between energy pathways through allowing modifications to be made at both ends of a pathway at the same time: sources for electricity are diverse and planned to become less fossil fuel dependent, whilst end uses can also be modified to suit. Electricity may thus allow the realignment of users with different energy resources, then one day be replaced with another energy carrier such as Hydrogen, should renewable sources of Hydrogen become the predominant source of supply.

Next, an analysis of national energy use in the UK was then conducted through the regrouping and ranking of energy use/users from the Digest of UK Energy Statistics (DUKES) report [3], where the electricity industry, domestic and road transport were found to be top users of energy, responsible for 23%, 19% and 18% of national energy use respectively. Through a qualitative assessment it was reasoned that Road transport was a primary target for change for these reasons:

- Road transport is exclusively dependent upon fossil fuels.
- There is a potential conflict of interest for use of the specific type of fossil fuel (petroleum products) that road transport is dependent upon; that conflict being between energy use for transport versus non-energy use, the latter being harder to substitute and arguably the larger priority for the preservation of civilisation especially if as expected future availability of or access to petroleum products is reduced.
- Road transport in the UK is predominantly responsible for the near-term local negative consequences of fossil fuel use (air pollution), because of the methods used by road transport to utilise energy from fossil fuels (combustion) and because location of use correlates and is proportional to population density.
- It was noted that there are already plans in motion to further reduce dependency upon fossil fuels for the electricity industry.

- It was more difficult to determine what, if any, change should apply to the domestic energy use/user group without full energy pathway consideration because electricity is a major constituent of that sector's energy use and heat, assumed to be the biggest purpose for fossil fuel energy use by the domestic sector, is a better match for heat and power grade biofuels to which indigenous biofuel production lends itself by virtue of the UK's native growing conditions.
- Road transport presently employs one primary energy conversion (chemical to kinetic), using one type of technology (internal combustion technology), with government regulation already playing a role in the design of vehicles whereas domestic energy use is diverse in purpose and technology, and is complicated by a variety of social factors.

When considering alternative energy pathways, electricity appeared to be the better energy option to replace fossil fuels for road transport – at least for the implementable immediate future in the UK. Hydrogen (H_2) is predominantly sourced from fossil fuels and a network for this fuel is further from implementation than the installation of recharging points for plug-in vehicles, meanwhile conflicts of interest over land-use, knock-on effects for land-use change abroad and continuation of air pollution caused by combustion leave transport-grade biofuels a lesser preference.

A well-to-wheel comparison for of petroleum products versus electricity as energy pathways for road transport demonstrated that there is a balance between energy mix and energy efficiency from well-to-tank, versus energy mix and energy efficiency from tank to wheel. In line with the importance of fossil fuel dependency, particularly the non-energy use of petroleum products highlighted earlier in the chapter, a method that incorporated energy mix in terms of fossil fuel dependency was designed and executed.

The findings from that method suggested that considering the well-to-tank part, more fossil fuel energy had to be input to the energy pathway for electricity than for petroleum products, to deliver the same amount of energy. Regardless of whether or not UKRES plans [4] for increased renewable electricity generation were considered, this was the case. When the tank-to-wheel part was considered, however, the reverse was true.

Coupling the two parts of the energy pathway analysis together, it was found that regardless of whether or not UKRES plans [4] for increased renewable energy in either pathway were considered, the electricity pathway led to a reduced use of fossil fuel energy. The end efficiencies of plug-in vehicles more than compensated for the inefficiencies of electricity generation and supply. Therefore: the electricity energy pathway for road transport in the UK is the better alternative for promoting the conservation of fossil fuels, particularly the types of fossil fuels that are of the greatest importance for conservation for non-energy purposes:

petroleum products. Rough figures were presented from the analysis that suggested a shift from petroleum products to electricity for UK road transport would result in a net reduction in fossil fuel use by road transport of:

- 42.6% without any of the changes proposed by the government in the UKRES [4] in energy mixes for *electricity* or *petroleum product* pathways
- 58.9% if electricity mix was improved according to the UKRES [4] whilst transport fuels remained unchanged
- 56.8% if both electricity generation and transport fuel mixes were improved according to the UKRES [4]
- 39.7% if transport fuel mix improved according to the UKRES [4] but electricity generation mix remained unchanged

Literature meanwhile advertised the promise of beneficial interactions between plug-in vehicles and the electricity supply system in the long-term future with regards to reducing fossil fuel use. This included proposals that plug-in vehicles could reduce the need for fossil fuel-based spinning reserves for peaking periods by targeting off-peak periods in existing electricity usage patterns, and that they could enable greater penetration of renewables into the electricity generation sector through the provision of vehicle-based ancillary grid services (V2G).

This further supported focus towards the shifting of road transport from fuel to electricity dependency. There was identified, however, a number of gaps in peer-reviewed and published research at the time. To begin with, there was a very strong absence of UK-based research in the field. What little there was had little or no focus upon the near-term implementation of a shift from fuel to electricity for road transport, excepting some distribution network levels studies. The social and behavioural constraints on the number of plug-in vehicles that could be adopted in the UK were almost completely ignored, with only cursory information used from the vast government study on national travel behaviour – the NTS [1].

10.3 SUMMARY OF CONTRIBUTIONS MADE TO THE FIELD OF STUDY

The Parry Tool was created. This tool draws together information from and basic analysis of multidisciplinary resources to check justification for interest in the electrification of road transport, and to inform plug-in vehicle load estimation and the design of recharging load management on a national scale, incorporating present limits to plug-in vehicle recharging demand scheduling as imposed by: the state of present technology, present human travel behavioural needs and existing patterns in electricity usage, into mitigation measures for deflecting (parrying) worst case scenarios. Included within the Parry Tool are the other contributions highlighted here.

An **NTS statistics extraction method** has been presented by which vehicle-focused travel behaviour statistics can be extracted from the people-focused National Travel Survey (NTS) [1]. This includes socioeconomic and travel behaviour-based estimates for vehicles eligible for replacement with plug-in kinds (using price and mileage range averages from the review of plug-in vehicle types mentioned above), scaled up to national estimates for ownership using national licensing statistics for UK road transport from the Transport Statistics Great Britain report (2009 edition) [7]. It also included vehicle travel behaviour statistics for those vehicles deemed eligible for replacement with plug-in vehicles, for use in modelling potential recharging behaviour and defining constraints (specifically the 'recharging window': the period of time between which a vehicle is not in use and can be recharged).

Recharging Regimes – a plug-in vehicle recharging demand management method, the product of design informed by The Parry tool – are another contribution of the project to the field. Recharging Regimes are a time-block approach to electricity demand management for plug-in vehicle recharging that prevents the exacerbation of existing demand peaks whilst offering load-levelling opportunities that could be implemented by vehicle owners, as opposed to relying upon the existence of a complex third party recharging load monitoring and control mechanism

Workday-to-weekend shifting of recharging loads was also presented here, building upon Recharging Regimes to incorporate the one pattern in UK electricity demand – the weekly pattern – that does not appear to have been considered before. It incorporates partial recharging into the Recharging Regimes so as to alter the distribution of recharging loads over weekly time periods to better reflect weekly patterns in existing electricity demand, adjusting recharging durations such that minimum requirements for next day's driving are met, plus allowance for an emergency reserve.

A **fossil-fuel focused well-to-wheel analysis** was introduced to provide a means of comparison of electricity and petroleum products energy pathways for road transport in the context of fossil fuel dependency to draw attention to the need to address the focus of modern research back to the cause of so many modern problems: fossil fuels, in particular: energy use of them.

An analysis method to find top energy use/users has been provided that regrouped energy use listed in the Digest of UK Energy Statistics (DUKES) Aggregate Energy Balance to provide a more useful dissection of purpose-centred energy use in the UK.

CHAPTER 11: PROJECT EVALUATION AND FURTHER WORK

This chapter provides an evaluation of the resources and tools used, as well as a more general evaluation of the findings in the context of the limitations of the methods used. The evaluation is used as a means to contribute suggestions for further work and future development. Consideration is given, lastly, to the transferability of findings from the applications of the Parry Tool to real life.

11.1 PROJECT EVALUATION

Methods were limited by the resources and tools used, and the time available to devise and carry them out. This evaluation considers the resources and tools used in the context of the methods that used them and notes, where relevant, compatibility issues where resources were used in combination.

11.1.1 EVALUATION OF PRIMARY RESOURCES USED IN PROJECT

This project used primarily four resources: The DUKES (Digest of UK Energy Statistics) reports [2] compiled by the DECC, the NTS (National Travel Survey) database compiled by the DfT and archived by the Economic and Social Data Service [1], half-hourly annual national electricity demand data available free online from National Grid [8] and lastly the websites and official Facebook pages belonging to vehicle manufacturers. What follows is a small discussion on their respective benefits and drawbacks as a resource for use in this particular project and potential further work.

11.1.1.1 Digest of UK Energy Statistics (DUKES) reports

The DUKES reports, although they contain estimated data and other uncertainties that might undermine the validity of conclusions drawn from investigating their contents, represent a unique and expansive resource that offered a great deal of insight into energy use in the UK. The use of the ktoe as a unit of energy proved useful when comparing energy use of different forms of energy across differing sectors. It was also more practical as a unit to handle figures of the scale of energy use for an entire nation.

Ideally more time would have been spent rigorously checking figures and the analytical methods trialled in the preliminary work that addressed secondary research questions – specifically the assessment of top energy use/users in Chapter 3 and the fossil fuel-based well-to-wheel analysis in Chapter 4. The assessment of top energy use/user groups in the UK is considered a very basic method that could be improved upon. It would perhaps have been better to have investigated the prospect of access to raw data for analysis from the DECC, rather than attempting instead to redefine groups of energy use/users from Aggregate Energy Balance Table presented in the report. The role of fossil fuels in the use of energy by different use/user groups would ideally be investigated in more detail; the fossil fuel-based well-to-wheel analysis for the comparison of energy pathways for road transport in Chapter 3 would provide a starting point for this. The assessment of energy users was fruitful because it highlighted the importance of including all electricity industry energy use together and that when this is done, the electricity industry constitutes the largest user of energy in the UK. It also highlighted the importance of road transport, which is almost exclusively dependent upon petroleum products.

Where DUKES report was used to contribute to a well-to-wheel analysis for changing the energy pathway for road transport from petroleum products to electricity, ideally a more rigorous method would have included more detail alluding, in particular, to the relative dependency upon petroleum products of the two pathways, for example through a fossil fuel focused life cycle analysis of plug-in vehicles. Again the method presented in this study is a very simple one, useful for getting a rough feel of the balance of two antagonistic factors: energy efficiency of end use, versus energy efficiency of provision of energy.

11.1.1.2 Vehicle manufacturer websites

Vehicle manufacturer websites were a valuable resource for information of the specifications of plug-in vehicles gathered in Chapter 5. Correspondence with administrators of official Facebook pages also proved useful for gaining swift clarification on points of interest. There was however plenty of confusion as different public facing parts of the same manufacturer might say different things about the same plug-in vehicle model. As a result it cannot be assumed that all specifications used in this study are correct, nor can it be assumed that these specifications will not change in time.

The manner in which vehicle information changes has also not been consistent, making it hard to keep track of how changes might impact upon the assumptions made in the research project. Caution is recommended in using manufacturer websites and in drawing conclusions from any research relating to specifications gathered from them, leeway should be given for the changeable nature of those specifications in future. Future work might include a sensitivity analysis of impact assessments based on plug-in vehicle specifications, to the changeability of those specifications over a given time period.

There was one piece of information that is lacking in the application of the Parry Tool to produce demand profiles for plug-in vehicle recharging (Chapter 8) that should have been included: proper recharging profiles for the batteries of each vehicle type. The assumption that recharging is linear is unrealistic, but information relating to the true state of affairs was hard to find from vehicle manufacturers. This represents a discipline that in future needs to be included in the Parry Tool: chemical engineering relating to battery technology. Further work would then consider the impact of these different rates of recharging with number of vehicles, timing of recharging in relation to existing demand, and especially for futuristic studies, how the profiles of aging vehicles may change over time.

11.1.1.3 National Travel Survey (NTS)

The NTS [1] has provided valuable insight into travel behaviour and the possibilities of being able to predict, not just react to, plug-in vehicle recharging. It was however difficult to manipulate for the use of vehicle behaviour analysis, primarily because the survey – in both data collection and organisation for display – is focused upon people and groups of people, not vehicles. The NTS contains a great deal of information that is not useful for this kind of study which must be selectively omitted. Meanwhile other information could be useful but is either unable to be used in a way that would suit the study, or is simply unusable, because of the structure of the NTS and the context of the questions it asks of survey participants as a result of its focus on people over vehicles.

When vehicle focused information was sought, additional steps became necessary that added substantially to processing time, especially where this concerned finding ways to get around the people-not-vehicles focus of the NTS. Examples include using a greater resolution of household income data that had to be sought out (was not already present in the database) from the DfT, and having to correct for the fact that vehicles listed in the Stages file do not match up directly with vehicles of the same number listed in the Vehicles file. This study provides the first written documentation of these problems although correspondence with the DfT staff that handle public enquiries about the NTS is strongly recommended for anyone looking to investigate the NTS for vehicle travel behaviour or ownership estimates.

The person – as opposed to vehicle – focus is particularly damaging when attempting to place in chronological order, records for individual vehicles so as to assess their travel behaviour, in particular to identify timings of travel and first or last departures. On one hand the NTS is a very pertinent reminder that variability is the nature of human behaviour – different people from the same household may exchange use of the same household vehicle during the day, meanwhile the NTS may also allow some ideas to be formed about the proportions of travel that do not start or end at home. On the other hand, there is no chronological sort that can be made to determine when a vehicle's first and last trip was performed.

'J3 - Journey Number' cannot be used to determine the first journey made by a vehicle. This is because a vehicle might first be used by one individual on a journey that is not their first of the day, but then by a different individual in the same household whose number of journeys during the day – at least at that point in time – number fewer than the first individuals. Thus meaning that the first journey that would be listed by a query could be second journey the vehicle made, not the first as it should have been.

Journey purpose – 'J24 - Journey Purpose From' or 'J26 - Journey Purpose To' – cannot be assumed to relate to first or last journey either. The starting destination of a vehicles journey may well be 'home' for most people, but this may not always be the case. Similarly the last journey made by the vehicle could end at a partner, relative or friend's house or a hotel, not necessarily 'home'.

Finally, the one variable that ought to be able to discern which journey came first would be the times for the journeys themselves – 'J54 - Journey Start Time (minutes past midnight - unbanded)' and 'J59 - Journey End Time (minutes past midnight - unbanded)' – but values for these are missing for some journeys for some vehicles. If they are missing for the first journey a vehicle makes, it would be easy to make a mistake when trying to chronologically order journeys so as to establish which came first and which came last. Also the only time data recorded is in the 'Trips' file, which means times are for journeys, not stages, which means that a journeys start time does not necessarily coincide with the start time of the vehicle stage within that journey.

There may be a way with careful querying or review of individual records, to compile a true list of journeys per vehicle, but there was not the time to do this in this study. So, a simpler method was used, accepting the errors that it could entail: simply remove all vehicles that had time missing data for depart from or return to 'home'.

Another problem arose when trying to produce graphs for the distribution of travel behaviour such as travel time versus distance travelled per day of the test week, or relating these to times of first departure or last return home. The NTS does provide times and distances both as continuous values and as banded values according to two different ranges. Unfortunately for considering possible recharging times for vehicles, the ranges provided for departure and return times would ideally be at the resolution of half an hour. They are not: the finest resolution grouping is hourly.

For distances travelled, the bandings are ranged in the opposite way that would be of use to this study. Distances less than 50 miles are banded finely, but in this study distances under 50 miles are assumed easily achievable for plug-in vehicles and so are not of concern. Larger distances, especially between 80 and 300 are of far more interest because depending on whether or not vehicles are recharged more often than just once a night at home, it is these distances that can make or break the decision to determine whether or not a vehicle is substitutable with a plug-in vehicle – PHEV or BEV – based on mileage. In the NTS distances between 50 and 100 miles are banded more coarsely than those under 50 miles and distances between 100 and 300 miles even more coarsely.

11.1.1.4 National Grid annual half-hourly demand data

Data acquired from National Grid [8] was very useful as a basis for analysis of patterns in national demand. The simple analysis conducted in Chapter 7 appears to be the first electricity demand analysis of its kind for having included consideration of the difference between minimum and maximum demand. In so doing, it may be the first to draw attention to the possible emerging growth in that difference over the years, a fact that will impact upon the need for ancillary services for sharper (increasing or decreasing at a faster rate) changes in load.

Fan et al [9] present an in-depth grouping method for analysing patterns in electricity demand but made no mention of this. Little was found in the way of demand pattern analysis elsewhere, as most sources tend to simply display demand as is, rather than taking daily averages or attempting to assess any changes in the difference between maximum and minimum demand. The 2011 SYS report [229] from National Grid makes mention of expectancy for increased ACS peaks, but makes no mention of the increasing difference between base-load and peak demand.

The analysis of existing demand patterns should ideally be replaced by an assessment of the importance and presence of localised patterns of electricity usage across the distribution network, scaling up then to the national level to ensure appropriate balances are kept in check. Accessibility to data for the analysis of electricity patterns across different parts of distribution networks does not seem to be widely available as a resource for researchers, which limits the inclusion of the heterogeneity of real life distribution networks in work of this kind. There are however examples to be found that illustrate its importance.

Woodbank Communications Ltd, a UK-based battery consultancy company, provides an ‘Electropaedia’ webpage [238] that includes a useful illustration that different types of demand (e.g. domestic, commercial, industrial) have different profiles that will be reflected at the local distribution level depending on where and which is dominant although these are dated 15 years ago and are only for one day. A report prepared for the DECC by BRE Ltd. [239], provides some useful graphs for the comparison of different load types for each quarter of 2006 in 2006.

With regards to the analysis of national demand, after the submission of this study for viva examination), a blog was produced by Euan Mearns [240] which usefully provides a similar breakdown of electricity demand as has been documented in this thesis, including an analysis of weekly demand patterns. These, like those in this study, were drawn from National Grid electricity demand data [8]. The blog also mentions an excellent (albeit privately provided and funded) resource: www.gridwatch.templar.co.uk [241], a website that was designed to:

> *"...scrape the data off the BMreports site every 5 minutes and inject it into an SQL database where it would be easy to perform specific searches and do statistical analysis. Then in a rather retro and humorous way, to display the data in terms of analogue instruments and moving graphs."*

- "About the Gridwatch Site" information page [242]

11.1.1.5 Issues arising from use of resources in combination

It is important to remember that none of the resources used in this project were designed with the others in mind. Certainly the data they hold was never intended for use in combination which led to a number of the issues specifically mentioned in reference to each in the subsections above. A particular problem was highlighted during the construction of the different scenarios introduced in this project, relating to the relative resolutions of data used.

It was foreseen that if National Grid electricity demand data was half-hourly, that departure from and return home times would need to be rounded to the half hour. However what was not foreseen was the argument relating to resolution of distances travelled, versus time required to recover this in equivalent SOC of a battery from recharging, versus the need for this to be given in half hourly intervals. In this study where rate of SOC recovered is assumed constant regardless of the SOC of a battery when recharging begins, one half hour recharging for a BEV equates to the recovery of 5% of the battery SOC, which is equivalent to 5.45 miles of range. The resolution of distances travelled by vehicles in the NTS is a tenth of a mile (0.1 miles).

This in turn led to rounding issues because during the estimation of recharging needs and the specifying of recharging durations in scenario 3, figures were rounded to the half hour, in other words, to 5.45 miles. This is why in 3A when recharging loads were shifted it appeared as though vehicles travelling the average plus SD mileage were receiving half an hour less recharging compared to vehicles travelling the same daily distances in 1B and 2B. It is also why in 3B when recharging loads were shifted it appeared that vehicles travelling average daily mileages were receiving half an hour more recharging than vehicles travelling the same distances in 1B and 2B. Ideally, electricity demand data would be at a resolution that reflects the amount of time it takes to recover 0.1 miles of equivalent battery SOC.

11.1.2 EVALUATION OF ANALYTICAL TOOLS USED IN PROJECT

Two internationally and highly accessible pieces of software were used to carry out the tasks in this study: Microsoft Excel and Microsoft Access from the Office 2007 package.

11.1.2.1 Merits and drawbacks of using Microsoft Excel 2007

On the whole, Excel performed exceptionally well for the tasks for which it was used throughout this study. From breaking down and reconstituting energy balances from the 2008 edition of the DUKES report [3] to determine top energy users and calculating pathway efficiencies, through to the simplistic analysis of annual National Grid half-hourly electricity demand data [8] and the design of Recharging Regimes.

Excel was however unsuited for handling the larger amounts of information contained in the NTS [1], to the point where even after extensive selection processes were carried out in Microsoft Access 2007 that narrowed down the number of fields and the number of records being investigated, it struggled to display travel data graphically. With a more powerful computer, however, this may not have been a problem. Having to use ‘minutes past midnight’ instead of a more easily recognisable time axis when displaying travel behaviour scatter graphs was less than ideal and made the graphs harder to interpret. Further work would include a review of the capabilities of alternative software packages to and check their suitability for the purposes of the Parry Tool.

11.1.2.2 Merits and drawbacks of using Microsoft Access 2007

Please note many of the following comments refer specifically to problems that were encountered using the Office 2007 edition of Microsoft Access, and that other editions and versions may not have these problems, or may have other problems not listed here.

Access has some useful functions. Whenever data was imported to or exported from an Access file, the import/export could be saved with a description. This was useful for noting what selection process was expected to have been included in the previous file for imports or what was expected to transpire and what had transpired in the open file to create the exports. It was also useful initially for getting to grips with what variables meant, noting for example that V112 is the variable that relates to vehicle ownership. Without these descriptions it would have been much easier to lose track of which variable had selection criteria applied and why, increasing the likelihood of mistaken application of criteria to the wrong but similarly named variable e.g. H70a versus H70.

Work was not conducted in a single Access file because of the sheer size of files it would have to have handled and the processing power required to conduct queries using those files once they were imported as tables. Splitting the selection process into several Access files was however incredibly useful, as each Access file was named according to the process step and adjustments could be made easily without affecting the rest of the task chain – albeit at the cost of time and effort in carrying those changes through once they were deemed to be satisfactory improvements.

One unexpected problem worthy of note was the fact that Access files tend to balloon in size when new data is imported or a new query run, because it keeps that size even when data is deleted. To save space, typically a file would be made to test a new part of the selection process, making all the errors there, then when the process and all necessary data was worked out a new Access was file copying the process in perfect order from scratch. The original file could then be deleted and the new file switched to ‘read-only’. As it happens, this proved an extremely wise thing to do as those files that were not being worked on and had been recreated and protected in this way were the only files recoverable when an accident lead to the loss of all saved project work.

Another point to note would be the disturbing tendency of Access to present answers to queries even when it has effectively given up on that particular query for lack of processing power. When handling the larger files and queries in Access it unwise to have other processes running in the background e.g. virus scans, as this can lead to a situation where a query is run, a result acquired, the computer shut down and rebooted again the next day only to find the same query run generates a different answer.

Nevertheless, considering that MS Access was used for this study in a way that it was never really intended to be used, to handle a method for extracting of vehicle-focused information from a survey that itself was never intended to be used for such a purpose, the software performed very well and informed the design of the NTS statistics extraction method.

11.2 FURTHER WORK

In this study, statistical analysis was sacrificed in favour of producing a broader strategic tool for synthesising information resources that had not been used in conjunction before, and for providing a basis upon which to design mechanisms for mitigating and managing plug-in vehicle loads. Greater depth of statistical analysis can be misleading unless greater depth in modelling factors influencing plug-in vehicle ownership and travel behaviour are investigated, but ideally a more in-depth study would specialise in investigating and drawing out more detailed statistics on ownership estimates and travel behaviour.

As recently noted in a study of actual plug-in vehicle usage behaviour (the CABLED trial) by researchers at Aston University and National Grid [183], use of plug-in vehicles by people can be quite varied. The NTS also reflected this. Ideally, variability in travel behaviour should be better incorporated and use of single average values for departure from and return to home times as well as daily mileages (which affect vehicle energy usage) should be avoided.

The researchers at Aston University and National Grid [183] noted not only that use of plug-in vehicles by people can be quite varied, but also recharging behaviour too – home is not necessarily the default recharging location. Plug-in vehicle recharging complements the domestic electricity demand profile nicely, but does it complement commercial or industrial demand profiles as well, or might it be the case that plug-in vehicle recharging on larger scales, are better restricted to home-only recharging? Either way, location of recharging needs to be considered, especially as numbers of recharging points outside of a plug-in vehicle's own home are increasing.

The NTS may provide some answers in this respect. It is an underutilised resource for plug-in vehicle research and there is plenty of room for improvement in the methods presented here, perhaps also to invent entirely new methods for vehicle-focused information extraction. Nevertheless given the problems encountered when seeking to determine vehicle-focused information highlighted earlier, there are problems that can be foreseen in attempting to establish vehicle recharging windows in relation to locations on a distribution network. More recent years of the NTS include information relating to parking location, but linking vehicle usage to a location on the electricity supply network may not be easy because of the protection of privacy and personally identifiable information about survey applicants and because survey questions will still be orientated from a household member's (not their vehicle) perspective.

There may be opportunity however to use the criteria within the NTS that handles journey purpose, to proxy this to different regions of an imaginary network with differing demand profiles. So a trip to "work" could be used to suggest the vehicle is parked at a location of the distribution network that has a commercial or industrial demand profile, whilst "home" suggests a region of the distribution network that likely has a domestic demand profile.

Nevertheless whilst the NTS provides some limited information about the destinations of journeys by listing their purposes, it provides little more than that. Studies based on actual plug-in vehicle behaviour such as the CABLED trial [183], although small scale, will play a more important role in determining locations for departures and destinations. Other studies that use the Time of Use Survey (TUS) for a more detailed investigation of how travel fits into other day-to-day human behaviour and activities, may help bridge the gap between the vast national coverage and archive of historical travel behaviour offered by the NTS, and the small-scale studies gathering intensive, vehicle-focused (not people-focused) information to build travel and recharging profiles.

Another area of further work might look into the prospect of differentiating between different BEV and PHEV and perhaps other vehicle types. This could be done by further segmenting the vehicle population by daily mileage to give a theoretical break down of e.g. BEV and PHEV to see how the different vehicle specifications attributed to the true variety of BEV and PHEV – not just theoretical standards for the two – might affect the shape and timing of loads given that departure from and return home times are somewhat tied also to the distances travelled by vehicles in a day. This combined with better information on battery recharging profiles, would provide a more realistic presentation of the population's potential recharging behaviour and would further inform the design of scheduling methods.

Research is also required that can look simultaneously at the granular differences in electricity demand across the differing topology of the electricity supply network and the 'big picture' national scale balance of supply and demand.

11.3 TRANSFERABILITY OF RECHARGING REGIMES AND RECHARGING LOAD-SHIFTING TO REAL LIFE SCENARIOS

Below are some of the contexts in which Recharging Regimes and load-shifting – the demand management methods designed from the information gathered by the Parry Tool – need further consideration.

11.3.1 TRAVEL BEHAVIOUR, UNRESTRICTED RECHARGING AND FOSSIL FUEL USE

Travel behaviour is far more varied than assumed in the project scenarios. Departure from and return to home times are averages taken from data with a very large spread. Nonetheless, Scenario 1 highlights the impact of simultaneous recharging when inappropriately timed to coincide with existing electricity demand peaks. Although perhaps they would not be as severe as shown in Scenario 1, the impact of unscheduled recharging could still have negative consequences, particularly in relation to the needs for regulation and spinning reserves, because typically it is fossil fuelled combustion generators that are better able to provide such ancillary services.

In other words, plug-in vehicles could theoretically *increase* the amount of fossil fuel used to provide electricity nationally, which would require a reassessment of the well-to-wheel comparison of the Electricity and Petroleum product energy pathways. More research particularly focusing on fossil fuel use increase and decrease in the UK is needed in every subject area, but considering how in this project both the 3 key energy (and fossil fuel) use/user groups in the UK are interrelated, particularly when considering a shift from transport fuels to electricity for road transport.

11.3.2 LEVELLING DEMAND ON TRANSMISSION AND DISTRIBUTION NETWORKS

What has been presented by this project – Recharging Regimes for plug-in vehicles – is a concept, not necessarily a working solution. As noted in Chapter 7 via industrial correspondence with R. Ferris, Innovation and Development Manager of Western Power Distribution: different sections of the electricity network experience different patterns in electricity demand. The national demand profiles used in this project are averages of these granular differences across the network topology, although it could be said that the national average is heavily weighted by the usage patterns of the domestic sector.

Further to this, R. Ferris highlighted that most of the present UK supply system was laid with foreknowledge that there are daily peaks – and lulls – in electricity demand. In particular, cyclical line ratings and cyclical component ratings are often used to determine what capacity of infrastructure should be laid, the point being that components and wires are tested and laid according to the assumption that there will be a peak followed by a lull which is used as a cool-down period.

It is unknown how valley-filling will affect the performance of network infrastructure. So, whilst hypothetically being a good idea for improving the efficiency of supply from fuelled generators by assuring a more constant output for those generators, electricity demand levelling could still require network reinforcement, although this may be considered a necessary and useful investment for the long term. More research is needed, likely in partnership with DNOs and National Grid, to check that hypothesis and investigate impacts of levelling demand locally and nationally in terms of performance of network infrastructure and costs (if determined necessary) of reinforcement.

11.3.3 IMPLEMENTATION OF RECHARGING REGIMES: MONITORING AND CONTROL

The implementation of Recharging Regimes has not been thoroughly investigated here, although it can be assumed that these regimes could theoretically be implemented by vehicle owners themselves, acting either manually to turn on or off recharging or by setting recharge timers for vehicles, at the behest of an external party. Perhaps a structure for ideal load could be provided to suppliers by designated network operators (DNO) and or National Grid, with the onus being placed upon suppliers to employ ways to influence their customers' electricity demand behaviour in the case of plug-in vehicle owners.

In [151] – a paper written alongside this project – it was proposed that as the UK does not yet have smart metering in place, Recharging Regimes could instead be arranged in contract. It was also noted that contractual arrangements would need to be simple to avoid customer confusion and stress regarding implementation of Recharging Regimes. In which case it is unlikely that Recharging Regimes implemented manually by drivers will be responsive to renewable electricity availability, because unless dispatch of renewable electricity generation is stored or predicted well in advance, such details could not be incorporated into contracts for recharge regime timings.

There would also be issues of accountability. How would a supplier know if their customer was abiding by their contract? How might the DNO be able to detect when plug-in vehicle users were breaking their contracts and recharging whenever they wanted, apart from when a problem arose?

Punishment is only effective if perpetrators can be identified and rules are only ever enforceable if there is accountability and consequence. Or are they..? There are subtle psychological methods for ensuring honest customer behaviour. The story of UK TV licensing is a great example of how to get around insufficient monitoring if people can be led to *believe* that there are ways for culprits to be detected and therefore punished [243]. If plug-in vehicle owners *believed* that suppliers know their electricity demand patterns and can detect if they are breaking their agreement, this would be just as good as enforcing the agreement through use of actual means such as smart metering.

As is slowly becoming the case for TV licensing, however, secrets can only remain secrets for so long, so there would be a future need for monitoring of either recharging (a task that could be performed by smart metering) or vehicle energy usage (which could be performed by in-car monitoring[20]). This is a good thing however, as it would lend weight to the 'market case' for development and roll-out of smart meters. In particular, smart meters that would ideally provide suppliers with sufficient daily electricity meter readings for them to assess whether customers with plug-in vehicles are recharging their vehicles as per their customer-specified Recharging Regime. Readings could be transmitted directly when taken or through some delayed data collection process. Regime-specific tariffs could then set patterns in electricity cost to encourage recharging to occur during a regime's prescribed recharging time.

11.3.4 LAYING THE FOUNDATIONS FOR FUTURE DEVELOPMENT OF VEHICLE-GRID RELATIONSHIPS

Where there is monitoring equipment, it is only a small step in terms of consumer acceptability to jump then to externalised control, in this case of recharge scheduling by a third party. The initial implementation of Recharging Regimes could be viewed as a training lead in

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[20] It should be noted that in-car monitoring systems are already in use in many new cars but there have been mixed responses from consumers, some of which raise privacy concerns [177].

this respect, proving to plug-in owners that someone can tell them when to recharge their vehicles and that this will not inconvenience them, where they remain assuredly in a position of complete control.

Once proven trustworthy, the implementation of Recharging Regimes would no longer be something to be carefully considered by the plug-in vehicle owner, but rather an inconvenience – “If only I had a gizmo that could set my timer for me, so I don’t forget and I still get all the benefits of having signed up for the contract...” This then provides an incentive to improve data collection on vehicle energy use – a prerequisite also for more complex vehicle-grid relationships to develop.

Armed with passive data collection regarding the location and timing of recharging demands, Recharging Regimes then could be tailored more carefully to match supply and demand. Use of Recharging Regimes could also then be monitored, with the next step being control of timing by a third party and finally if proven feasible, the development of other services like V2G.

Nevertheless, caution must be taken as to how monitoring and control are presented to the public. More UK-based research must be done in this area focusing on plug-in vehicles, as well as investigating the impact of social factors upon plug-in vehicle adoption predictions. Needs for privacy and anonymity constrain surveys like the NTS that look in detail at human behaviour and smart metering has already faced a backlash for related reasons [178]. Location-related information may be a grey area for privacy, although car manufacturers are already finding ways to turn collection of such information into a tool for drivers to use for themselves, thus justifying collection e.g. the Nissan LEAF [212].

In short: Recharging Regimes are not the final solution or final form for establishing a mutually beneficial relationship between road transport and the electricity industry. They are instead a precursor to the smart technology that is expected to follow.

APPENDIX 1: NTS – VEHICLE OWNERSHIP

As noted in Chapter 6: not all information for all criteria of interest in this study can be located in one file, so several files had to be linked together to gather the information required. Due to the large size of the NTS, this included a long series of record selections conducted one after the other in a series of steps, eliminating records prior to bringing in additional information as the process continued. Multiple Access files were generated to do this. This allowed process steps to be checked carefully and streamlined the overall process so as to avoid processing errors due to file-size management issues that will be mentioned in the evaluation at the end of this chapter.

Determining factors for plug-in vehicle ownership for this study were limited to household income and the mileages travelled by household vehicles per day of the travel week. Thresholds for ownership follow on from work done in Chapter 5 (see Fig. A1.1).

Fig. A1.1. PHEV specifications used for establishing PHEV ownership and BEV specifications used for establishing BEV ownership drawn from Chapter 5.

A sequence of queries were run to establish numbers of BEV and PHEV eligible vehicles from the travel records of vehicles listed within the NTS and these are documented in this section of the chapter: first selecting for income, then selecting for daily mileage. Those numbers will then be scaled up to represent matching proportions of the total number of vehicles licensed to drive on UK roads in 2008 as according to the TSGB 2009 edition by the DfT [7], in the last part of this section.

SELECTING FOR INCOME

First the Household .txt file had to be imported into Microsoft Access, creating a table of the records it contained. The only point to note as regards the import process was the way in which the Primary Key for a table was set up and this was the case for all imports made in the process of the project. Instead of allowing Access to create a Primary Key, the Primary Key was made after finishing the import process using several fields that in combination were unique to each record in the table.

In order to do this it is important that during the import process to ensure no fields are 'indexed' and then uncheck the option for Access to create a Primary Key. A primary can then be set by looking at the imported table in 'Design view', selecting the rows that represent the fields that in combination are unique for every record in that table, which can then be set as the Primary Key by right clicking on the selection and clicking 'Primary Key' on the menu that appears. The Access file was then saved under the name 'Select1_Hh_status_h70a' because it was to be the first part of the selection process (Select1), using the NTS tab-delimited file named Household (Hh), running queries based on two criteria: survey participation (status) and household income (h70a).

The first task was to eliminate households that did not fully co-operate with the survey, as whilst much of their data may be of use to other users of the NTS, they lack complete travel data necessary for this study and so must be removed. Next a query needed to be created to select records relating to households based on their recorded incomes. In the NTS Household file, the variable for income is 'H70A - Household Income' and has the following criteria:

- '0' = 'Less than £25,000'
- '1' = '£25,000 to £49,999'
- '2' = '£50,000 and over'
- '3' = 'NA'

Note that this is for total household income, not disposable income. This banding for income was deemed insufficient for any useful assessment of plug-in vehicle ownership. So after consultation with the Darren Williams from the NTS team at the DfT, an additional tab-delimited text file was acquired that provided a higher resolution income banding for households in the survey. The new variable was named 'H70' with criteria listed in Table A1-1.

Table A1-1: List of criteria values and associated band widths for variable H70 – a higher resolution banding of household income provided by the Darren Williams of the NTS team at the Department for Transport.

Criteria value	Banding	Criteria values (continued)	Banding (continued)
0	Less than £1000	12	£15000 – £17499
1	£1000 – £1999	13	£17500 – £19999
2	£2000 – £2999	14	£20000 – £24999
3	£3000 – £3999	15	£25000 – £29999
4	£4000 – £4999	16	£30000 – £34999
5	£5000 – £5999	17	£35000 – £39999
6	£6000 – £6999	18	£40000 – £49999
7	£7000 – £7999	19	£50000 – £59999
8	£8000 – £8999	20	£60000 – £69999
9	£9000 – £9999	21	£70000 – £74999
10	£10000 – £12499	22	£75000 or more
11	£12500 – £14999	23	NA

From this new list of criteria and after consideration of the prices of plug-in vehicles noted in Chapter 5 it was decided that households with incomes greater than £30,000 - £34,999 would be eligible for plug-in vehicle ownership. This additional .txt file was also imported into a table and then a relationship was created between the new, finer-banded household income file and the household file (see Fig. A1.2). The file name was changed to reflect this addition, becoming ‘Select1_Hh_status_h70_dwilliams’ in reference to the source of the additional information: Darren Williams of the NTS team at the DfT.

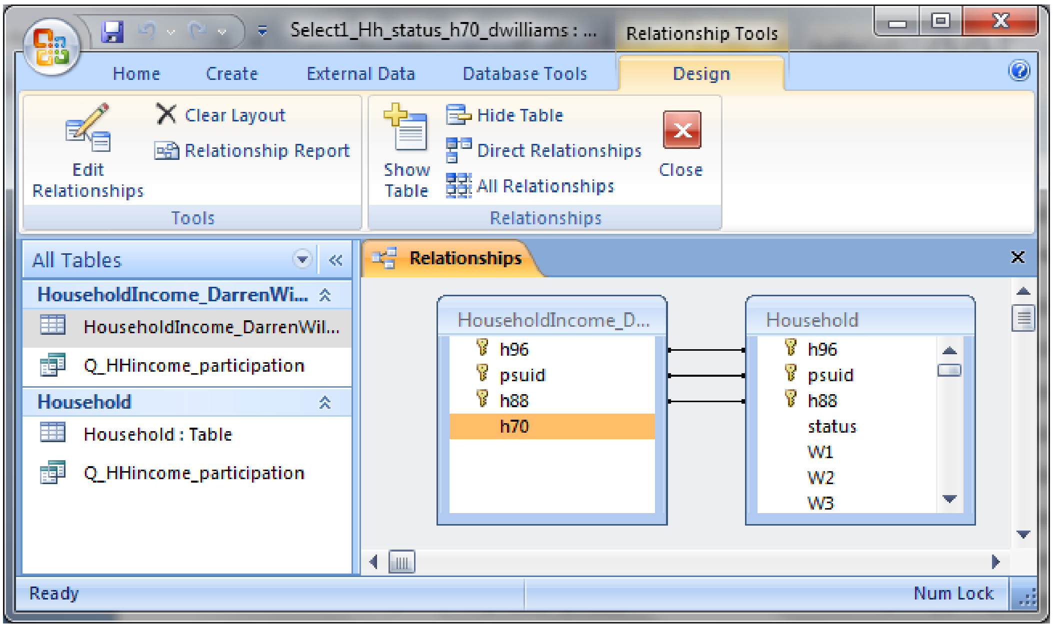
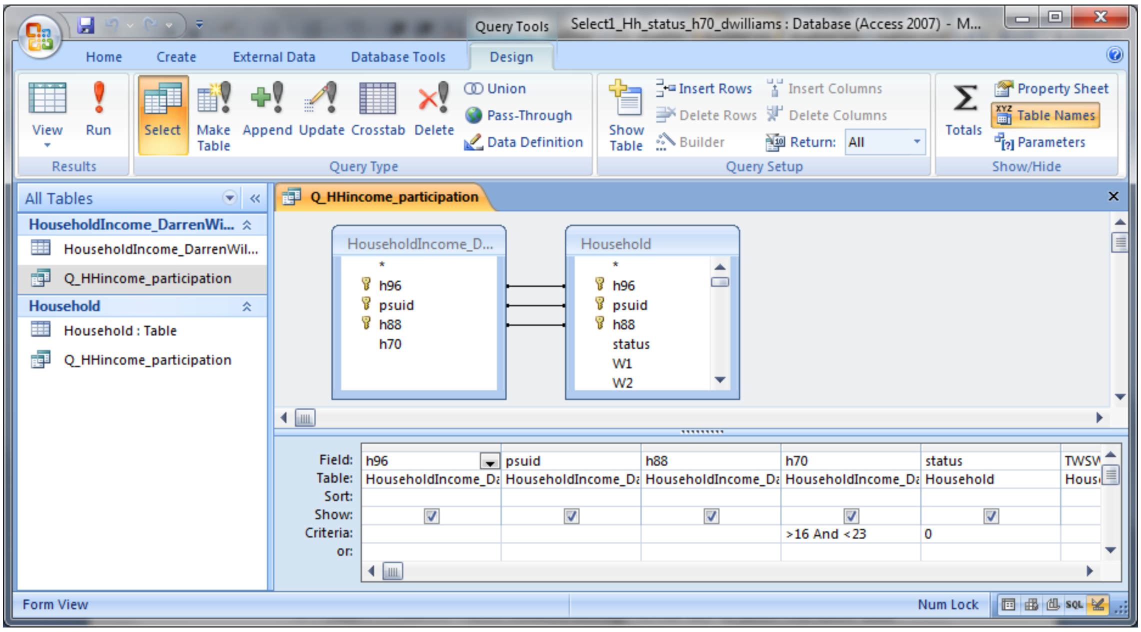


Fig. A1.2. Creating a ‘relationship’ between the table for ‘Household’ from the NTS database and the supplementary table for household income supplied by Darren Williams, member of the NTS team at the DfT. Note that key symbols indicate fields that were used to define primary keys for each table.

Once the relationship was in place, a query could be made to select households listed in the ‘Household’ table based on their corresponding income listed in the new ‘HouseholdIncome’ table. In the query, households were selected by the criteria “>16 And <23” in the field ‘H70’ for income and “0” in the field ‘Status’ to ensure only households fully co-operating in the NTS were selected (see Fig. A1.3).



Field:	h96	psuid	h88	h70	status	TWSV
Table:	HouseholdIncome_Da	HouseholdIncome_Da	HouseholdIncome_Da	HouseholdIncome_Da	Household	Hous
Sort:						
Show:	☑	☑	☑	☑	☑	
Criteria:				>16 And <23	0	
or:						

Fig. A1.3. Creating a query to select Household records belonging to households earning £35,000 or more per year and selecting only households that “fully participated” in the survey.

63952 households were listed in the original Household tab-delimited text file. After selecting only those that fully co-operated in the survey, 57069 remained. 28.67% of those records remaining – 16361 to be precise – were records for households earning £35000 per year or more, hence forth shortened to "≥£35k/a". After the query was run, the results were exported to a tab-delimited text file named 'Select1_output' ready for use in identifying vehicles.

IDENTIFY PRIVATE VEHICLES

First a correction had to be made to the existing Vehicle file, because 'V1 - Vehicle Reference Number' does not match up directly with the identification of which vehicle was used for stages in a journey in the Stage file. This is because the criteria for 'V1 - Vehicle Reference Number' do not match up to 'S22 - Whose Vehicle?' – see Table A1-2.

Table A1-2: Criteria mismatch for identifying vehicles in Stages and Vehicle NTS files.

Value	V1 - Vehicle Reference Number	S22 - Whose Vehicle?
'0'	No.1	Non-Household veh.
'1'	No.2	Household vehicle 1
'2'	No.3	Household vehicle 2
'3'	No.4	Household vehicle 3
'4'	No.5	Household vehicle 4
'5'	No.6	Household vehicle 5
'6'	No.7	Household vehicle 6
'7'	No.8	Household vehicle 7
'8'	No.9	Household vehicle 8
'9'	No.10	Household vehicle 9
'10'	No.11	Household vehicle 10+
'11'	No.12	NA
'12'	No.13	DNA
'13'	No.14	-
'14'	NA	-
'888'	Multipunched	Multipunched
'999'	No answers	No answers

In order to make the two variables match up, The Vehicles file - which is around two percent of the size of the Stage file – was imported into Microsoft Excel. Then a new column was added – ‘V1NEW’ – and a simple function copied into all cells which took the value of the ‘V1’ column and added one[21].

This modified Vehicle file was then imported from Excel into a new Access file named ‘Select2_V_v1NEW_v112’. A query was then run with selecting the criteria “<10” for the field ‘V1NEW’, which ensured only singular household vehicles that could be matched up to those listed in the Status file remained.

74505 vehicles were listed in the original Vehicles tab-delimited text file. By limiting household vehicles to listing only up to the 9th vehicle a household could own, 74503 vehicles remained. The only two vehicles that were lost were the tenth vehicles belonging to two different households. With the correction to ‘V1’ made, vehicles could then be selected for private ownership.

In Chapter 5 it was reasoned that vehicle ownership may influence the likelihood of that vehicle being a plug-in vehicle. Prior to consultation of the NTS there was concern that the study was concentrating solely on cars, when smaller vehicles, in particular for example motorbikes and scooters, also have plug-in variants in development. It was discovered however that information relating to ownership of non-four-wheeled vehicles does not feature in the NTS. Only information for four-wheeled vehicle ownership was collected in the survey, so the argument to include more than just four-wheeled vehicles was considered mute on the basis that data for non-four-wheeled vehicles was not available anyway.

Ownership was assumed to be biased against plug-in vehicles where company cars were concerned for reasons described in Chapter 5. As such, private ownership was deemed a necessary pre-requisite for considering whether or not a vehicle could be replaced with a plug-in substitute. A query was set up to select vehicles based on ownership information included in the Vehicles file under the field ‘V112 - Company Car Summary’. The criteria for ‘V112’ are as follows:

- ‘0’ = Company car/ any free fuel
- ‘1’ = Company car/ no free fuel
- ‘2’ = Self-emp. business car
- ‘3’ = Employer pays some private costs
- ‘4’ = Used for work/ ICOW allowance only
- ‘5’ = Used for work/ no allowance

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[21] This correction was suggested and approved by the NTS team for the DfT.

- ‘6’ = Not used for work/ 3 yrs old or less
- ‘7’ = Not used for work/ over 3 yrs old
- ‘8’ = Other non-company car
- ‘9’ = DNA (not a 4-wheeled car)
- ‘888’ = Multipunched
- ‘999’ = No answers

Selection criteria thus applied to the ‘V112’ field to select records with values “>1 And <9”, which excludes non-four-wheeled vehicles, company cars – be they with or without fuel paid for by the company – and any records where this field has either been multipunched or not answered by respondents. Self-employed business cars were included because the user of the vehicle is also the same person that decides what type of vehicle they can have. After selecting for private ownership, 62174 vehicle records remained – representing roughly 83.45% of the vehicle population sampled by the NTS[22]. Having completed the query, the results were exported as a tab-delimited text file saved as ‘Select2_output’.

MATCHING VEHICLES TO THEIR HOUSEHOLDS

In a new Access file, named ‘Select3_VandHh_match’, the results from the previous two steps – ‘Select1_output’ listing the records for households selected based on income and ‘Select2_output’ listing vehicles selected based on ownership – were imported. Their tables were then linked through a relationship (see Fig. A1.4).

A query was then run which matched vehicles to households with the same values for ‘H96 – Sample year’, ‘PSUID – PSU (Primary Sampling Unit) Identification Number’ and ‘H88 – Household reference number’. The results of the query thus displayed only information for the 37.32% of privately owned vehicles – 23205 to be precise – found to be belonging to those households with incomes of ≥£35k/a. These vehicles were distributed between 14474 households. The results of the query were exported into a tab-delimited text file named ‘Select3_output’.

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[22] The two vehicles that were the 10th vehicles for their households that were excluded earlier and so were not included in this query were checked and both were categorised as ‘9’ – DNA (not a four-wheeled car).

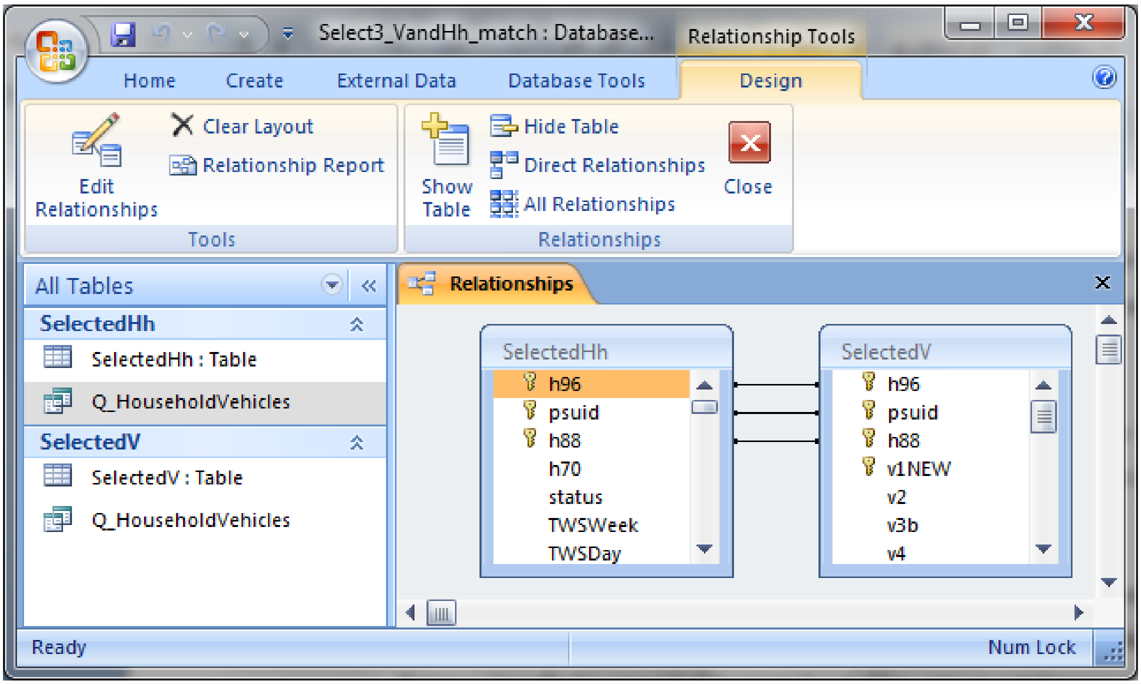


Fig. A1.4. Creating a 'relationship' between the tables for selected vehicles and selected households, so as to enable a query to be run to find selected vehicles and selected households that have matching records, thus excluding any vehicles belonging to households that were not listed and vice-versa.

SELECTING FOR DAILY MILEAGE

The next task was to identify journeys made by household vehicles belonging to selected households, determine the daily mileages of those vehicles by summing the journeys they made in a day, then apply criteria from Chapter 5 to establish which vehicles could not be substituted with plug-in vehicles and for those that could, which could be substituted with a BEV and which with a PHEV. A careful sequence of record linkages and queries must be made to carry out this task, because the necessary information is spread out between several files.

SELECTING STAGES BELONGING TO DRIVERS

The next step was to begin looking at travel information, in particular to locate records where household members were driving household vehicles. The NTS focuses on people, not vehicles, so for example there can be multiple record entries for a single vehicle making the same journey, because the vehicle contained several individuals from the household. As such, an intermediate step is required to select only records that relate to a household member driving a vehicle. The key variable of interest for this task is located in the Stage file was 'S18 - Private Vehicle Occupant', the criteria for which are as follows:

- '0' = Front passenger

- ‘1’ = Rear passenger
- ‘2’ = Passenger (front/rear unknown)
- ‘3’ = Passenger (2007 onwards)
- ‘4’ = Driver
- ‘5’ = NA
- ‘6’ = DNA
- ‘888’ = Multipunched
- ‘999’ = No answers

The Stage file was imported into a new Access file, named ‘Select4_S_s18’. A query was then made where driving records for were selected by inputting the criteria value “4” for the field ‘S18 - Private Vehicle Occupant’. This eliminated any stages that were made without the use of a vehicle and any stages made using a vehicle by an individual who was not themselves the driver. Please note that at this point ‘stages’ have not been linked to household vehicles, nor have they been linked to households of a particular income range. 1044511 stages were identified as stages made by household members driving vehicles, accounting for 46.85% of all journey stages recorded for the NTS. The results of the query were exported into a tab-delimited text file named ‘Select4_output’.

MATCHING STAGES MADE BY HOUSEHOLD DRIVERS TO HOUSEHOLD VEHICLES

Not all stages made by household members are made using household vehicles, so stages made by household drivers using non-household vehicles must next be removed. Previous selection results ‘Select4_output’ which listed stage data selected for household drivers and ‘Select3_output’ which lists privately owned four-wheeled vehicles selected for belonging to households earning ≥£35k/a, were imported into a new Access file, named ‘Select5_S_HhV_match’. A relationship was then created between the two (see Fig. A1.5) and a query run to find matching records.

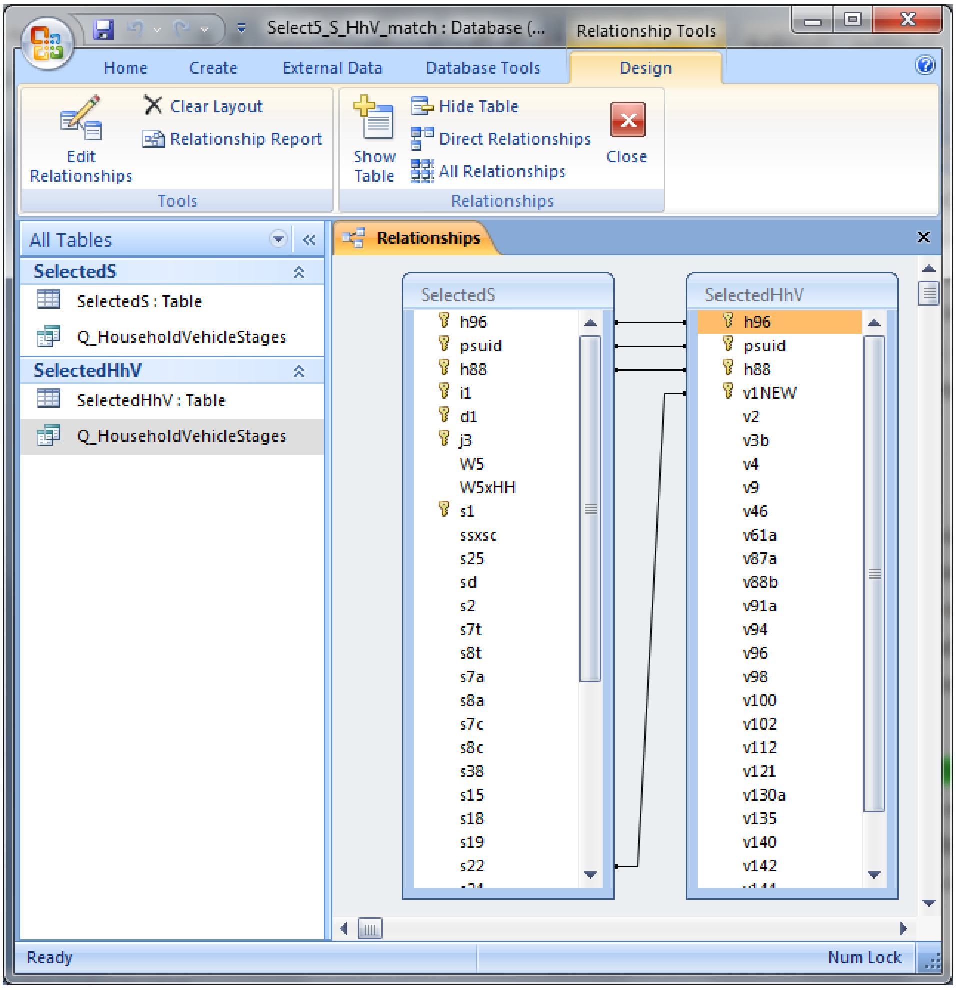


Fig. A1.5. Creating a relationship between the table named “SelectedS” (tabling results ‘Select4_output’) for selected Stage records and the table named “SelectedHhV” (tabling results ‘Select3_output’) for records from previously selected Vehicles belonging to previously selected Households.

36.45% of the 1044511 stages identified as driver stages – 380726 records – were for household drivers using household vehicles from households earning ≥£35k/a. These stages were attributed to 21287 vehicles, belonging to 13927 households. The results of the query were exported into a tab-delimited text file named ‘Select5_output’ ready for use in the next step.

FINDING MATCHING TRIP DATA TO ENABLE ‘PER DAY OF THE WEEK’ MILEAGE ANALYSIS

There is a variable missing in Stage that is required to work out daily mileages: the variable that marks for what day of the week a travel record was made. The variable ‘D1 - Travel Day’ is present in the Stage file, but this variable notes only which day of the ‘travel week’ a journey took place. Not all respondents started their survey – the beginning of which marks the beginning of their travel week – on the same day of the working week e.g. Monday. On which day of the working week travel was recorded is, however, recorded in the Trips file by the variable 'TRAVDay – Travel Day of the Week'.

So, the previous collation of 'stage' data from specified 'vehicles' belonging to specified 'households' needed to be supplemented with 'trip' data in order to attribute travel to specific days of the week before daily mileages per vehicle could be calculated. Results from the previous step – ''Select5_output' – which contains stages travelled by household drivers using household vehicles belonging to households earning ≥£35k/a – and the Trips tab-delimited .txt file of the NTS were imported into a new Access file named 'Select6_T_HhVS_match'. A relationship was made between the two (see Fig. A1.6) and then a query was run to match trips to journey stages recorded for the selected vehicles belonging to the selected households.

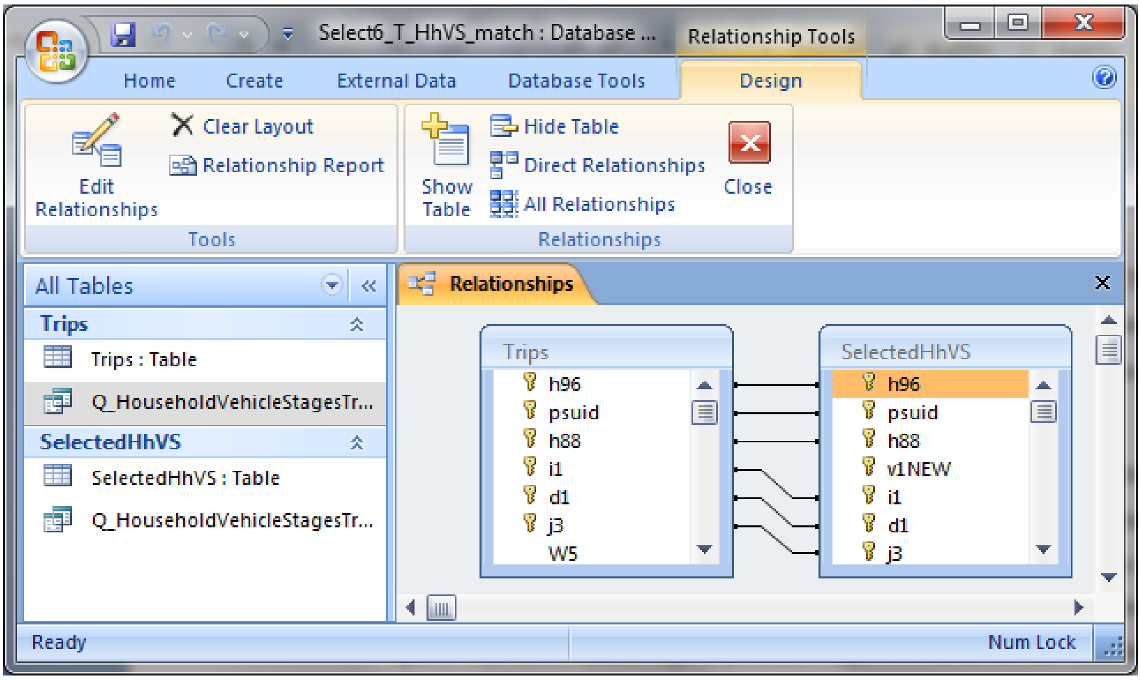


Fig. A1.6. Creating a relationship between the table containing Trip records (which includes the criteria 'TRAVDay – Travel Day of the Week') and the table containing all the Household, Vehicle and Stage information selected previously based on income, type of vehicle and which individual was the driver of that vehicle for each Stage record.

All 380726 stages had matching trip records. They were divided between 380390 trips indicating that some trips involved more than one stage made by a household vehicle. This will be important later when considering the timing of journeys made by vehicles, because times are provided for trips but not stages within trips, so trips that consist of more than one stage – be that by different household vehicles or some combination between household vehicles and other modes of travel like train or walking – provide only the departure and arrival times of the person for the whole journey which is thus not necessarily the same as that for the vehicle. The results were exported to a tab-delimited text file named: ‘Select6_output’.

ESTABLISHING DAILY MILEAGES FOR VEHICLES

Having collected the travel data – including stage and trip information – for vehicles that fit the right criteria for ownership and belong to households with the right income to be potential plug-in vehicles and having attributed to each record a day of the working week, the next step requires the assessment of daily distances travelled.

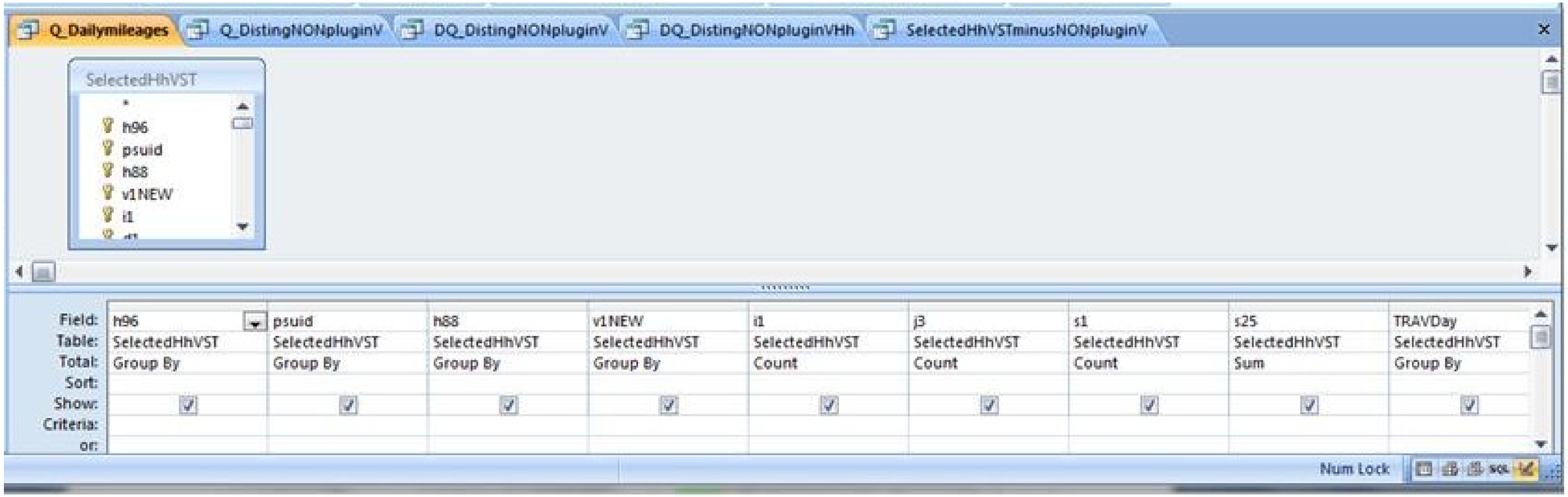
Daily mileage as a variable is not included in the NTS, but distances travelled for different stages of different trips are and these are attributed a time, day and date. The measurement of distance travelled is provided in several variables, as continuous values but also as values banded into discrete ranges. This study used the variable that provided continuous data, which was ‘S25 - Stage Distance (tenths of miles – unbanded)’. Measured in tenths of miles, an example value of 110 would equal a distance of 11 miles.

In order to calculate daily mileages for selected vehicles, the results of the previous step – ‘Select6_output’ which includes stage and trip data for the selected vehicles belonging to selected households – were first imported into a new Access file named ‘Differentiate1a_HhVST_ICEV’, then several queries were made. The first query performed the task of grouping records by adding a “Totals” row and then under the following fields selecting the instruction “Group by”:

- ‘H96’ – Sample year
- ‘PSUID’ – PSU (Primary Sampling Unit) Identification Number,
- ‘H88’ – Household reference number and
- ‘V1NEW’ - Vehicle Reference Number (corrected to match with ‘S22 – Whose vehicle?’.

Those four fields together enable the identification of travel data for specific vehicles so if a ‘sum’ function is input to another field, it will sum values for that field per vehicle. Records also needed to be ‘grouped by’ the field “TRAVDay” – short for ‘Travel Day of the Week’ – to see the distances travelled by vehicles during journeys on different days of the week. Finally, added into the Totals row beneath the field ‘S25’ – Stage Distance (tenths of miles - unbanded) – was the sum function. See Fig. A1.7 for a snapshot of the query.

The result of this query grouped data into 112807 records that show how many miles in total different vehicles travelled on different days. The next step will be to begin dividing vehicles according to their daily mileages into vehicles that may be substituted by plug-in vehicles and those that may not.



Field:	h96	psuid	h88	v1NEW	i1	j3	s1	s25	TRAVDay
Table:	SelectedHhVST	SelectedHhVST	SelectedHhVST	SelectedHhVST	SelectedHhVST	SelectedHhVST	SelectedHhVST	SelectedHhVST	SelectedHhVST
Total:	Group By	Group By	Group By	Group By	Count	Count	Count	Sum	Group By
Sort:									
Show:	☑	☑	☑	☑	☑	☑	☑	☑	☑
Criteria:									
or:									

Fig. A1.7. Query used to determine daily mileages of the selected vehicles per day of the week.

DISTINGUISHING NON-PLUG-IN VEHICLES BY DAILY MILEAGES TRAVELLED

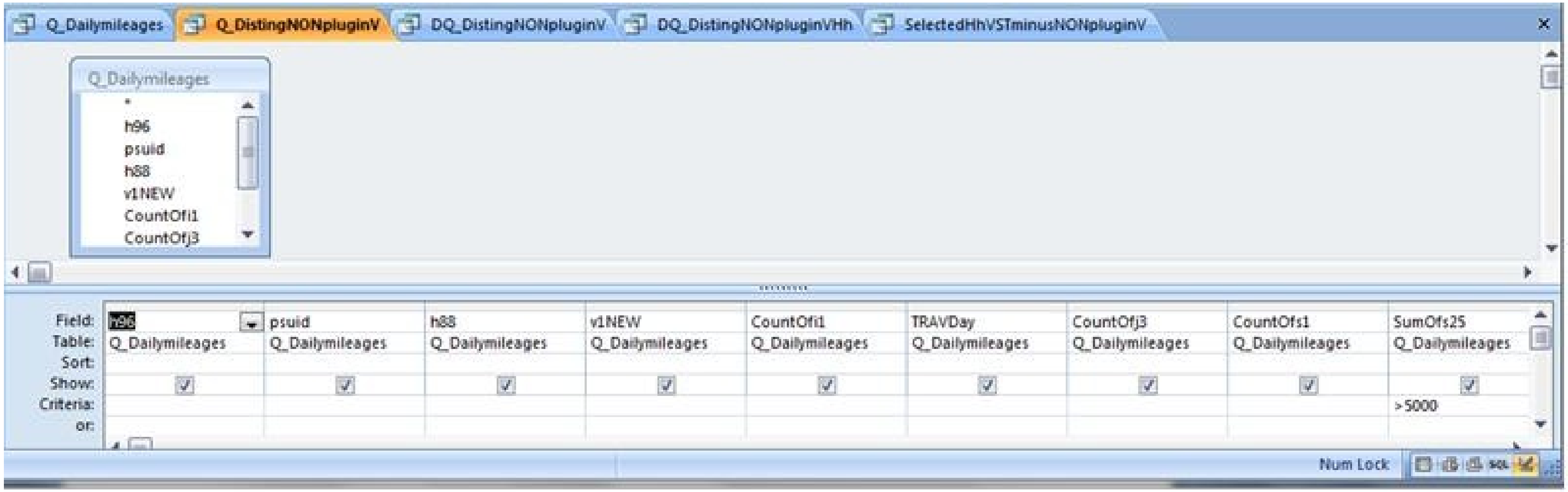
Daily distance travelled (daily mileage) is used as an indicator for vehicle energy usage in this study, the idea being that if a vehicle travels more than a plug-in vehicle manufacturer suggests one of their vehicle can travel on a full battery, then that vehicle would be unwise to replace with a plug-in vehicle. In the NTS, vehicles that could or couldn't be replaced with a BEV or a PHEV would be differentiated by the distances they have travelled on the days of the travel week, with the assumption made that the travel week is typical for their travel behaviour.

Specifications for vehicles to be judged by maximum daily mileage were drawn from Chapter 5 (averaged across the vehicles in the study sample for BEV and PHEV). As such, the parameters for distinguishing which vehicles could be substituted with a plug-in vehicle were as follows:

- BEV = vehicles whose summed mileage on any day totalled 100.6 miles or less
- PHEV = vehicles whose summed mileage on one day or more was more than 100.6 miles, but no greater than 500.0 miles on any day
- ICEV (non-plug-in vehicles excluded from further study) = any vehicle whose summed mileage on any day exceeded 500.0 miles

The first task was to identify and remove records for vehicles that travelled too far on any day to be replaceable with a PHEV or BEV, i.e. travelling further than 500.0 miles on any day of the week. In order to distinguish between vehicles based on these parameters, the NTS must be queried to indentify vehicles in the order of ICEV, PHEV then BEV. This is because shorter distances are not exclusive to vehicles travelling under 100.6 miles on any day, so all three vehicles will likely have records for the shortest journeys. It is possible to do the process the other way around, but the number of steps changes little and the complexity of the selection process likewise.

Using the same Access file that was used to generate the daily distances travelled by vehicles – 'Differentiate1a_HhVST_ICEV' – a new query based on the first was generated to select records for vehicles travelling more than 500.0 miles on any day (see Fig. A1.8). This query however omits the other records for the same vehicles where those vehicles were travelling lesser daily mileages. It also included multiple records for the same vehicles where those vehicles travelled more than 500.0 miles on more than one day. A simple count of records therefore does not say how many vehicles the query has identified.

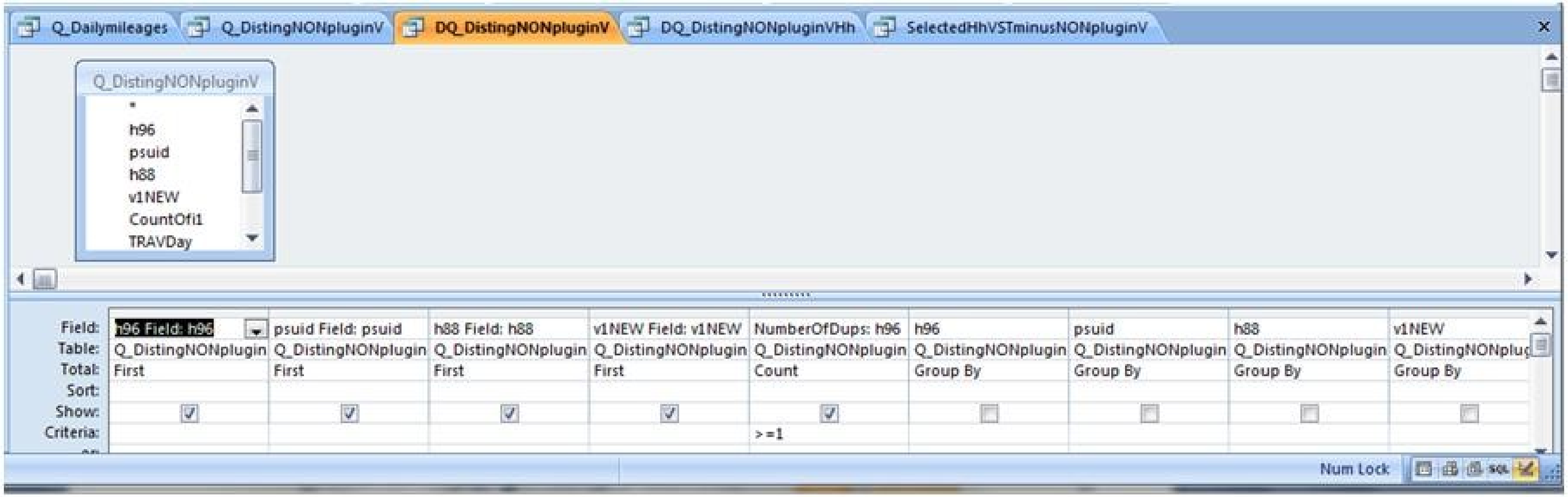


Field:	h96	psuid	h88	v1NEW	CountOfi1	TRAVDay	CountOfj3	CountOfs1	SumOfs25
Table:	Q_Dailymileages	Q_Dailymileages	Q_Dailymileages	Q_Dailymileages	Q_Dailymileages	Q_Dailymileages	Q_Dailymileages	Q_Dailymileages	Q_Dailymileages
Sort:									
Show:	☑	☑	☑	☑	☑	☑	☑	☑	☑
Criteria:									>5000
or:									

Fig. A1.8. Query selection criteria used to identify records for vehicles travelling more than 500 miles in a single day.

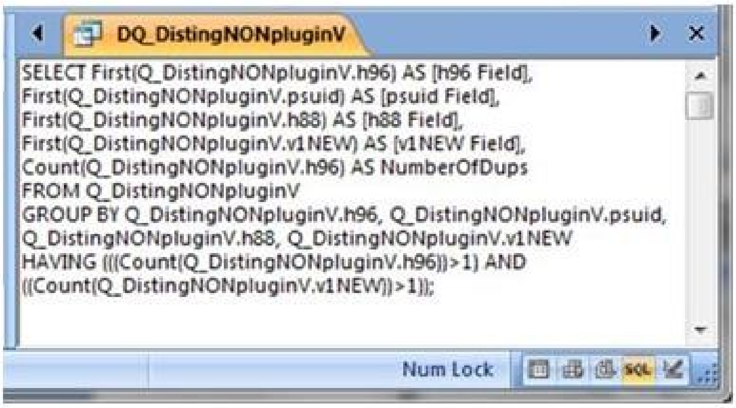
Another query was needed to create a list of these vehicles. This query was a ‘duplicates query’ – a type of query that would normally be used to identify duplicate records in a database created for example by accidentally entry of the same record twice. Ordinarily a duplicates query would omit records that do not have duplicates. In order to generate a list of vehicles identified by the distance query, the duplicates query was edited to list records with one or more identical copy (see Fig. A1.9).

The complete SQL (Structured Query Language) code of the altered duplicates query and the default are compared in Fig. A1.10 and Fig. A1.11. In Fig. A1.11 it can be seen that where “>1” featured in the line of code for “HAVING....” that this was edited as “>=1”. As can be seen in Fig. A1.9-A1.11 the fields chosen for the duplicates query were those that identify individual vehicles, namely: ‘H96 – Sample year’, ‘PSUID – PSU (Primary Sampling Unit) Identification Number’, ‘H88 – Household reference number’ and ‘V1NEW’ as the replacement for ‘V1 - Vehicle Reference Number’.



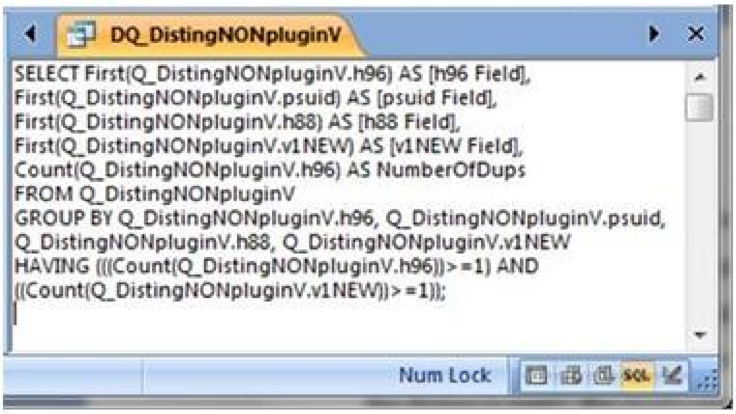
Field:	h96 Field: h96	psuid Field: psuid	h88 Field: h88	v1NEW Field: v1NEW	NumberOfDups: h96	h96	psuid	h88	v1NEW
Table:	Q_DistingNONplugin	Q_DistingNONplugin	Q_DistingNONplugin	Q_DistingNONplugin	Q_DistingNONplugin	Q_DistingNONplugin	Q_DistingNONplugin	Q_DistingNONplugin	Q_DistingNONplu
Total:	First	First	First	First	Count	Group By	Group By	Group By	Group By
Sort:									
Show:	☑	☑	☑	☑	☑	☐	☐	☐	☐
Criteria:					> =1				

Fig. A1.9. Modified duplicates query in ‘Design View’ which when run will generate a list of individual vehicles.



```
SELECT First(Q_DistingNONpluginV.h96) AS [h96 Field],
First(Q_DistingNONpluginV.psuid) AS [psuid Field],
First(Q_DistingNONpluginV.h88) AS [h88 Field],
First(Q_DistingNONpluginV.v1NEW) AS [v1NEW Field],
Count(Q_DistingNONpluginV.h96) AS NumberOfDups
FROM Q_DistingNONpluginV
GROUP BY Q_DistingNONpluginV.h96, Q_DistingNONpluginV.psuid,
Q_DistingNONpluginV.h88, Q_DistingNONpluginV.v1NEW
HAVING (((Count(Q_DistingNONpluginV.h96))>1) AND
((Count(Q_DistingNONpluginV.v1NEW))>1));
```

Fig. A1.10. Automatic SQL code generated after selecting to run a “Duplicates Query”. This code will return a count of the number of times the same combination of values for the variables ‘h96’, ‘psuid’, ‘h88’ and ‘v1NEW’ occurs. Under this coding, where a record has a combination that matches no other record for these criteria, it will not be listed.

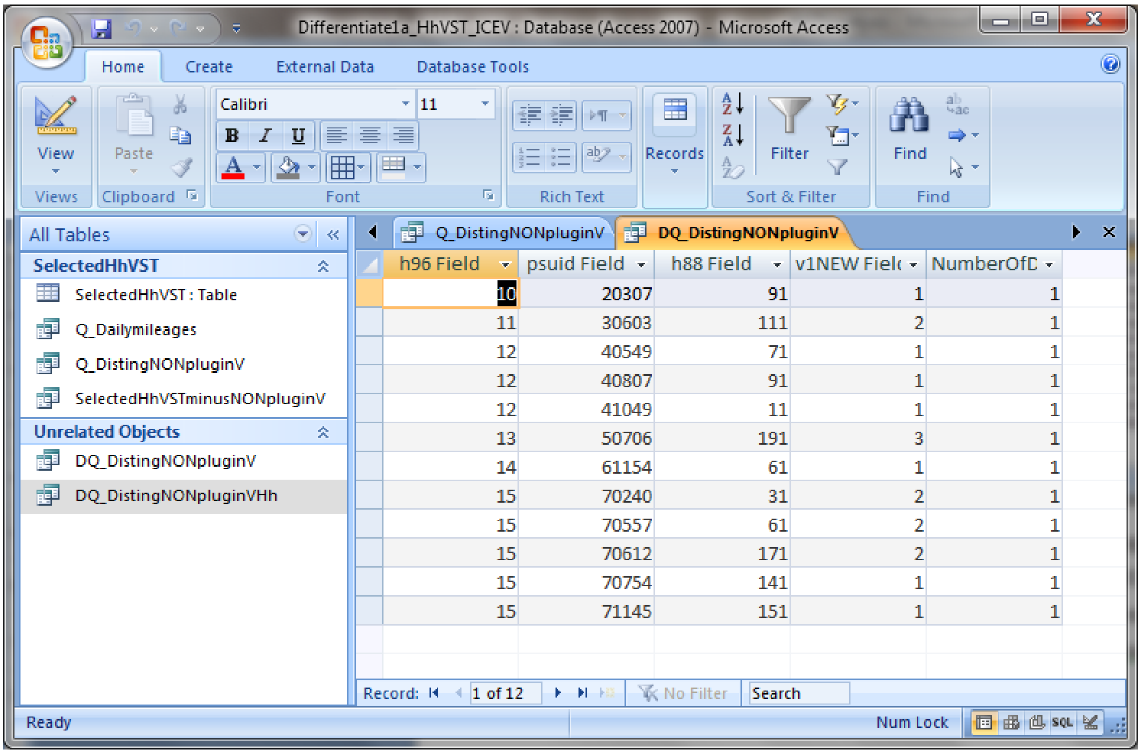


```
SELECT First(Q_DistingNONpluginV.h96) AS [h96 Field],
First(Q_DistingNONpluginV.psuid) AS [psuid Field],
First(Q_DistingNONpluginV.h88) AS [h88 Field],
First(Q_DistingNONpluginV.v1NEW) AS [v1NEW Field],
Count(Q_DistingNONpluginV.h96) AS NumberOfDups
FROM Q_DistingNONpluginV
GROUP BY Q_DistingNONpluginV.h96, Q_DistingNONpluginV.psuid,
Q_DistingNONpluginV.h88, Q_DistingNONpluginV.v1NEW
HAVING (((Count(Q_DistingNONpluginV.h96))>=1) AND
((Count(Q_DistingNONpluginV.v1NEW))>=1));
```

Fig. A1.11. Demonstration of how the automatic SQL code generated when selecting to run a ‘Duplicates Query’ can be changed so that instead of counting only incidences of duplication, it returns a list of all the different combinations of those variables that exist in the records, ignoring duplicates.

The query identified 12 vehicles (see Fig. A1.12) – representative of approximately 0.06% of the 21287 vehicles for which travel records were available. These 12 vehicles belonged to 12 different households (each has a different combination of ‘H96’, ‘PSUID’ and ‘H88’).

So, vehicles that have been identified as travelling distances per day too large to allow them to be replaced by a plug-in vehicle have now been listed. Next the records for these vehicles need to be removed so that further queries can be run to identify vehicles that could be replaced with PHEV versus those that could be replaced with BEV. This was done by using an ‘unmatched query’.



h96 Field	psuid Field	h88 Field	v1NEW Fiel	NumberOfD
10	20307	91	1	1
11	30603	111	2	1
12	40549	71	1	1
12	40807	91	1	1
12	41049	11	1	1
13	50706	191	3	1
14	61154	61	1	1
15	70240	31	2	1
15	70557	61	2	1
15	70612	171	2	1
15	70754	141	1	1
15	71145	151	1	1

Fig. A1.12. Results of customised 'Duplicates Query' listing the 12 vehicles that travelled more than 500.0 miles on one or more days of the week.

An 'unmatched query' would normally be used to identify records with missing values where they tie across more than one table in an Access database. For example: imagine a restaurant keeping tabs of customers and orders. In their Access database they have tables for entries for both. Every customer should have one order or more but judging from the sizes of the tables in their database ("Customers" having more records than "orders") clearly there have been some mistakes made in data-collection. The task set by the restaurant manager in this example would therefore be to find records for "Customers" that have no corresponding records for "Orders". In this case, an unmatched query would fulfil this requirement.

For this study however, this kind of query was used in a slightly different way – it has been tagged onto the end of a selection process to generate a list of records containing only those of interest. Having identified a list of vehicles that cannot be replaced with plug-in vehicles, an unmatched query was used to pull records that relate to all vehicles *excluding* records that relate to the vehicles on that list. Recall that 'SelectedHhVST' refers to the imported results 'Select6_output' that relates trip records to stages travelled by household members driving household vehicles, from households earning ≥£35k/a, the coding for the unmatched query is as follows in Fig. A1.13.

```
SELECT SelectedHhVST.h96, SelectedHhVST.psuid, SelectedHhVST.h88,
SelectedHhVST.v1NEW, SelectedHhVST.i1, SelectedHhVST.d1, SelectedHhVST.j3,
SelectedHhVST.W5, SelectedHhVST.W5xHH, SelectedHhVST.s1, SelectedHhVST.ssxsc,
SelectedHhVST.s25, SelectedHhVST.sd, SelectedHhVST.s2, SelectedHhVST.s7t,
SelectedHhVST.s8t, SelectedHhVST.s7a, SelectedHhVST.s8a, SelectedHhVST.s7c,
SelectedHhVST.s8c, SelectedHhVST.s38, SelectedHhVST.s15, SelectedHhVST.s18,
SelectedHhVST.s19, SelectedHhVST.s22, SelectedHhVST.s24, SelectedHhVST.s24a,
SelectedHhVST.s29, SelectedHhVST.s30, SelectedHhVST.s33, SelectedHhVST.s34,
SelectedHhVST.s36, SelectedHhVST.s37, SelectedHhVST.sttxsc, SelectedHhVST.s39,
SelectedHhVST.s21, SelectedHhVST.s40, SelectedHhVST.s41, SelectedHhVST.TRAVDay,
SelectedHhVST.TRAVDD, SelectedHhVST.TRAVMM, SelectedHhVST.TRAVYYYY,
SelectedHhVST.j14, SelectedHhVST.j37, SelectedHhVST.jjxsc, SelectedHhVST.j36,
SelectedHhVST.j36a, SelectedHhVST.j23, SelectedHhVST.j24, SelectedHhVST.j26,
SelectedHhVST.j28, SelectedHhVST.j28a, SelectedHhVST.j29, SelectedHhVST.j30,
SelectedHhVST.jttxsc, SelectedHhVST.j32, SelectedHhVST.j33, SelectedHhVST.jotxsc,
SelectedHhVST.j54, SelectedHhVST.j55, SelectedHhVST.j59, SelectedHhVST.jdungross,
SelectedHhVST.jd, SelectedHhVST.j57g, SelectedHhVST.j58g, SelectedHhVST.jtotcost,
SelectedHhVST.j62
```

Part 1

```
FROM SelectedHhVST LEFT JOIN DQ_DistingNONpluginV ON (SelectedHhVST.h96 =
DQ_DistingNONpluginV.[h96 Field]) AND (SelectedHhVST.psuid =
DQ_DistingNONpluginV.[psuid Field]) AND (SelectedHhVST.h88 =
DQ_DistingNONpluginV.[h88 Field]) AND (SelectedHhVST.v1NEW =
DQ_DistingNONpluginV.[v1NEW Field])
WHERE (((DQ_DistingNONpluginV.[v1NEW Field]) Is Null));
```

Part 2

Fig. A1.13. SQL code generated when selecting to do an ‘Unmatched Query’ in order to make a list of household-vehicle-stage-trip records that do not include any associated with vehicles previously found to have travelled more than 500.0 miles on any one day of the week.

The section of code in Part 1 of Fig. A1.13 lists the fields from records that will be given in the query results. That first piece of code comes from the table containing the records you want to keep. The second section of code in Part 2 of Fig. A1.13 tells Access to take the records from the table ‘SelectedHhVST’ – the fields in particular listed above in yellow highlight – and what to do with them, relating to a combination of fields from the duplicates query that distinguished non-plug-in vehicles, ‘DQ_DistingNONpluginV’.

Of the 380726 stage records with trip data that existed for household drivers driving household vehicles from households earning ≥£35k/a, 190 were for vehicles that had during their travel week travelled more than 500.0 miles on one day or more. The exclusion of records for these vehicles left 380536 records. The next step will be to pull from these vehicles identified as potentially replaceable with PHEV and BEV. The results were exported to a tab-delimited text file named ‘Differentiate1a_output’.

DISTINGUISHING POTENTIAL PHEV AND BEV BY DAILY MILEAGES TRAVELLED

The results from the previous step – ‘Differentiate1a_output’ – which included only travel records for vehicles that could be replaced with either PHEV or BEV – were imported into a new Access file named ‘Differentiate1b_HhVST_PluginV’. The selection process for distinguishing non-plug-in vehicles was then repeated using this data in order to distinguish PHEV from BEV eligible vehicles. The entire process was repeated exactly but for one difference: where the non-plug-in vehicles were distinguished by having one day or more where they were travelling 500.0 miles or over, PHEV eligible vehicles were distinguished by having one day or more where they were travelling over 100.6 miles.

The removal of PHEV eligible vehicle records in the final unmatched query left only travel records for vehicles deemed suitable for replacement with a BEV. 3352 PHEV eligible vehicles were distinguished from 17923 BEV eligible vehicles. These were representative of 15.75% and 84.20% of the total population of vehicles that had travel records – 21287 – from households earning ≥£35k/a. The PHEV eligible vehicles were distributed between 3074 households, the BEV eligible vehicles were distributed between 12521 households.

The results of the unmatched query that displayed records relating to BEV eligible vehicles only were exported into a tab-delimited text file named ‘Diff1b_BEVrecords’. Then yet another unmatched query was used to extract PHEV eligible vehicle records using the results of the unmatched query to find BEV eligible vehicle records. Records for PHEV eligible vehicles were then exported to a tab-delimited text file named ‘Diff1b_PHEVrecords’. These records now selected, are ready for the second part of establishing vehicle-focused statistics from the people focused NTS: determining daily mileages and time data for first departure and last return home for each day of the working week as will be shown in the next part of this appendix.

APPENDIX 2: NTS – TRAVEL BEHAVIOUR

There are two components of travel behaviour considered in this study: mileage travelled and the timing of departure and return to home per day on each day of the week. All vehicles selected in Appendix 1 have associated Stage and Trip records. All vehicles have distance data recorded in 'S25 - Stage Distance (tenths of miles - unbanded)' from the Stage tab-delimited text file and an associated 'TRAVDay - Travel Day of the Week'.

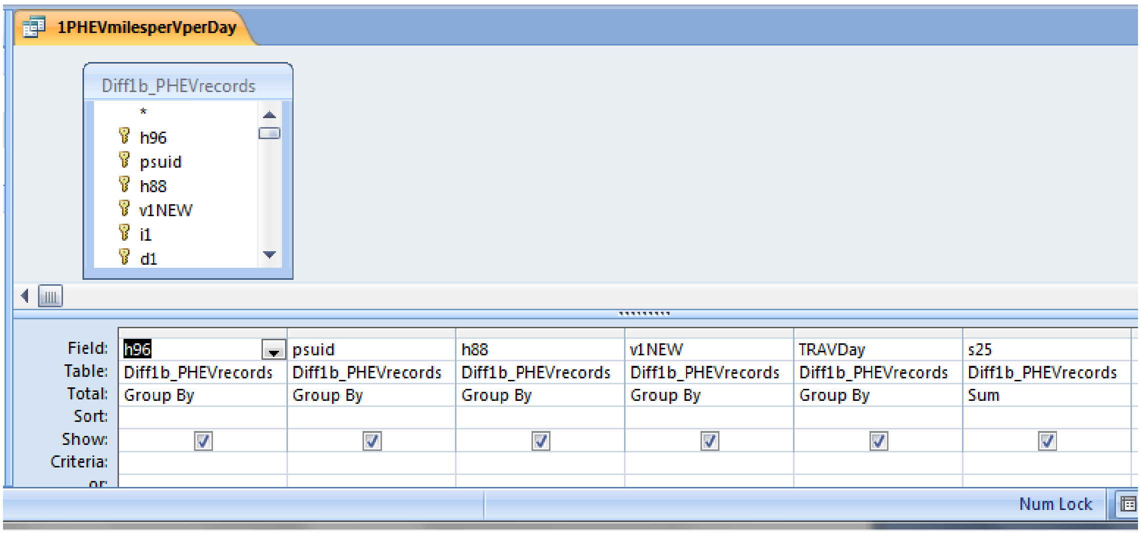
Theoretically in their Trip data each should also have values recorded for 'J24 - Journey Purpose From' and for 'J26 - Journey Purpose To', along with corresponding values for 'J54 - Journey Start Time (minutes past midnight - unbanded)' and for 'J59 - Journey End Time (minutes past midnight - unbanded)'. Unfortunately they do not.

Fortunately of concern to this study are only the 'start time' and 'journey purpose from' for the first journey and the 'end time' and 'journey purpose to' for the last journey, made by each vehicle on each day of the working week. Even so, there were still vehicles that had to be dropped because they were missing appropriate information and this will be detailed in the selection processes in this section.

In this section, first mileage statistics and then first departure and last return per day of the week will be compiled for PHEV and BEV eligible vehicles. Then a brief analysis of compiled travel behaviour for each will be presented. Finally a summary of the statistics that will be carried through to the next stage of the study – the construction of scenarios for plug-in vehicle recharging – will be provided.

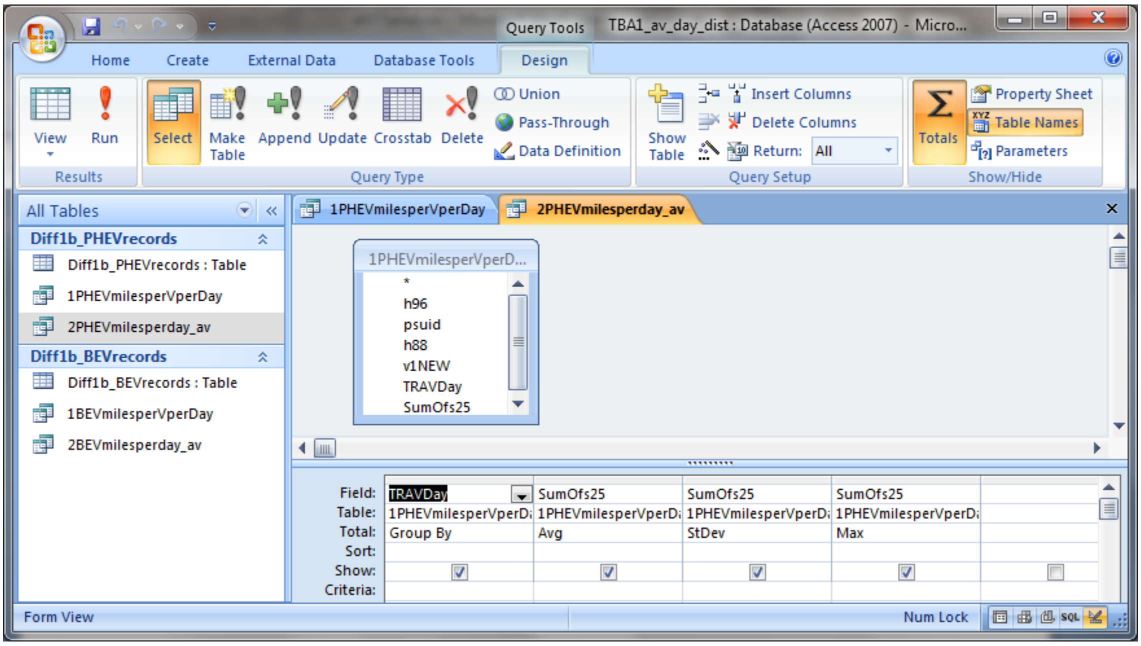
COMPILING MILEAGE STATISTICS

A new Access file was created for mileage-based travel behaviour analysis, named 'TBA1_av_day_dist'. Imported into this file as tables were the results from the last stage of analysis done to identify BEV and PHEV eligible vehicles, namely the results that list records for these vehicles: 'Diff1b_BEVrecords' and 'Diff1b_PHEVrecords'. Daily mileages were calculated as before – see Fig. A2.1 for example. Basic statistics – the mean average, SD and maximum mileage – were then collected per day of the week in a new query (see Fig. A2.2).



Field:	h96	psuid	h88	v1NEW	TRAVDay	s25
Table:	Diff1b_PHEVrecords	Diff1b_PHEVrecords	Diff1b_PHEVrecords	Diff1b_PHEVrecords	Diff1b_PHEVrecords	Diff1b_PHEVrecords
Total:	Group By	Group By	Group By	Group By	Group By	Sum
Sort:						
Show:	☑	☑	☑	☑	☑	☑
Criteria:						

Fig. A2.1. Calculating daily mileages vehicles deemed replaceable with PHEV in order to gather statistics on miles travelled per day of week.



Field:	TRAVDay	SumOfs25	SumOfs25	SumOfs25	
Table:	1PHEVmilesperVperD	1PHEVmilesperVperD	1PHEVmilesperVperD	1PHEVmilesperVperD	
Total:	Group By	Avg	StDev	Max	
Sort:					
Show:	☑	☑	☑	☑	☐
Criteria:					

Fig. A2.2. Calculating mean average, Standard Deviation (SD) and maximum mileages per day of the week for vehicles deemed replaceable with PHEV.

Results are reported in Part 3 of the NTS statistics extraction method in Chapter 6. PHEV eligible vehicles travelled slightly longer distances over weekends (Friday to Sunday) although across the population their travel behaviour also became more variable as SD also increased for mileage on these days. Maximum mileage reported varied over the week (73 mile difference between shortest versus longest maximum mileages recorded) for PHEV, but for BEV the variation was far less – only of the order of a few tenths of a mile or so.

Averages and SD for BEV changed over the week but were far more consistent, although there was a slight trend towards longer journeys in the week versus weekend, with slightly more variability (slightly larger SD) on weekends. Given the sample sizes for PHEV and BEV, these trends might be worthy of further investigation, but the SD speaks volumes of the natural variability of human behaviour in real life situations and that variability should always be taken into account.

COMPILING DAILY FIRST DEPARTURE FROM AND LAST RETURN TO HOME STATISTICS

In this study, departure time is assumed synonymous with the time that vehicles must have completed recharging by and the latest time they might be found to be recharging. Meanwhile return home times are assumed synonymous with the earliest time vehicles might be found to be recharging.

As noted previously, not all vehicles that have matching travel data have the necessary information to be able to identify the times of their first departures from and last return returns to home on each day of the working week. Vehicles that had missing times for either were deemed un-useable. So these first had to be removed, then analysis of departure and return times could begin.

REMOVE VEHICLES WITH MISSING DEPARTURE FROM AND RETURN TO 'HOME' TIMES

As noted previously, journeys are made up of stages that can include stages from other forms of transport. Journeys are per person, not per vehicle, Journeys are grouped and numbered according to individuals, stages within journeys are grouped and numbered in the same way: according to journeys made by individuals. Times are given for journeys, not stages. Also some journeys have missing times. It thus extremely difficult to identify, at least for a particular vehicle, its first or last journey that vehicle made and the start or end times for those journeys.

In order to generate first departure and last return time statistics for vehicles, despite the potential for errors (which will be detailed in the evaluation part of this chapter – 6.3) a very basic assumption was made. That assumption being that within records with the value '22' – coding for 'home' – in variables 'J24 - Journey Purpose From' and 'J26 - Journey Purpose To' would be contained the first and last journeys made by vehicles. The time for the first departure from home was assumed to be synonymous with that for a vehicle's first journey of the day. The time for the last return to home was assumed to be synonymous with that for the vehicle's last journey of the day.

First a new Access file was created named 'TBA2_missingtimes'. Records for PHEV and BEV eligible vehicles – the same tab-delimited text files 'Diff1b_BEVrecords' and 'Diff1b_PHEVrecords' as were imported to the previous file – were imported into separate tables. According to the documentation, 'J24 - Journey Purpose From' and 'J26 - Journey Purpose To' have the same possible values/coding shown in Table A2-1.

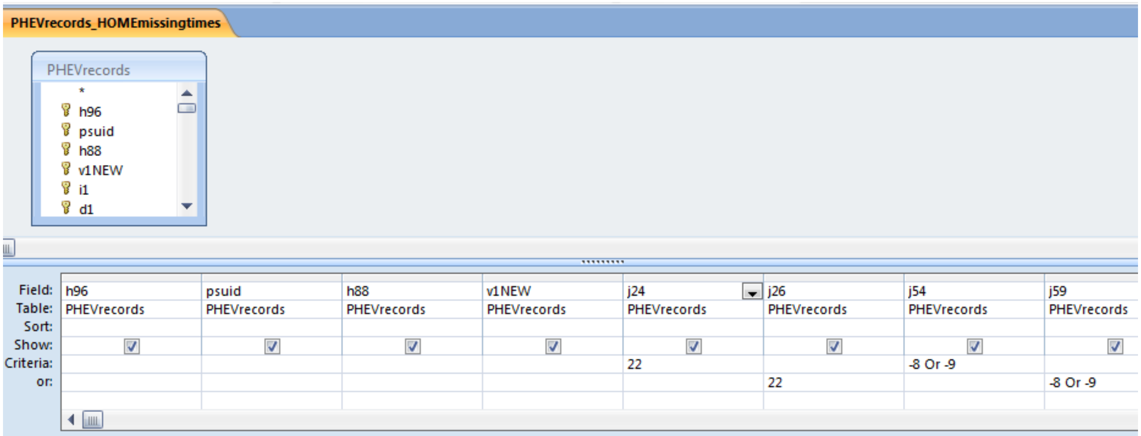
Table A2-1: List of criteria values for the variables 'J24 - Journey Purpose From' and 'J26 - Journey Purpose To'.

Criteria value	Banding	Criteria values (continued)	Banding (continued)
0	Work	13	Holiday: base
1	In course of work	14	Day trip/just walk
2	Education	15	Other non-escort
3	Food shopping (from 1998)	16	Escort home
4	Non food shopping (inc. food shopping before 1998)	17	Escort work
5	Personal business medical	18	Escort in course of work
6	Personal business eat/drink (from 1995)	19	Escort education
7	Personal business other	20	Escort shopping/pers. business
8	Eat/drink with friends (inc. pers. bus. eat/drink pre-1995)	21	Other escort
9	Visit friends	22	Home
10	Other social	23	NA
11	Entertain/public activity	888	Multipunched
12	Sport: participate	999	No answers

In two queries – one for each the BEV and the PHEV eligible tables of records, 'Home' which is assigned the value '22' in both variables, was first criteria applied. The query hunted for records with the value '22' in either variable. Next to the query was added the criteria to look for missing times associated with journeys. For both variables 'J54 - Journey Start Time (minutes past midnight - unbanded)' and 'J59 - Journey End Time (minutes past midnight - unbanded)' the coding for missing values were:

- '-8' = DNA
- '-9' = NA

So, the query was adapted, as exampled by Fig. A2.3 showing the query for PHEV eligible vehicle records, to find records with ‘22’ as the value for J24 and ‘-8 Or -9’ for J54 and to find records with ‘22’ as the value for J26 and ‘-8 Or -9’ for J56. The premise being that identifying the vehicles to which the records listed in the results for this query will show vehicles with missing time data for either their first departure or their last return home.



Field:	h96	psuid	h88	v1NEW	j24	j26	j54	j59
Table:	PHEVrecords	PHEVrecords	PHEVrecords	PHEVrecords	PHEVrecords	PHEVrecords	PHEVrecords	PHEVrecords
Sort:								
Show:	☑	☑	☑	☑	☑	☑	☑	☑
Criteria:					22		-8 Or -9	
or:						22		-8 Or -9

Fig. A2.3. Modification of query to find records for travel from and to “home” that did not have missing times. It is assumed that these journeys represent the first and last journeys in a day made by vehicles.

Next a duplicates query was used to list the vehicles to which those records related. Then an unmatched query was used to extract only records belonging to vehicles other than those listed by the duplicates query, thus displaying results only for vehicles that did not have missing time data. This process of elimination was carried out for both PHEV and BEV eligible vehicles. 304 PHEV and 1509 BEV eligible vehicles had missing time data, leaving 3012 PHEV and 16414 BEV eligible vehicles. Records for PHEV and BEV eligible vehicles identified as having complete time data for departure and arrivals were exported to tab-delimited text files named ‘TBA2_PHEVrecords_fulltimes’ and ‘TBA2_BEVrecords_fulltimes’.

IDENTIFY VEHICLES FOR WHOM ALL JOURNEYS WERE SINGLE STAGES AND SO HAVE CORRECT TIME DATA

As previously stated: departure and arrival times are noted for journeys in the NTS, but not for stages within journeys. Ideally, within the subset gathered in the previous step, even vehicles whose journeys involved more than one stage could be used. Vehicle records could still be included in the average for first departure and last return home times if on any day both of the following points are true:

- the vehicle's first 'from home' journey listed the household vehicle stage as being the first stage of that journey – meaning that the start time logged for that journey would also be the start time of the first vehicle stage
- the vehicle's last 'to home' journey listed the household vehicle stage as being the last of that journey – meaning that the end time logged for that journey would also be the end time of the last vehicle stage

Unfortunately there is no chronological order given for vehicle stages, only for journeys and these are not necessarily the journeys of the vehicles but of the individual people surveyed in the household. So the only way to know for sure which were the first stages a given vehicle was used to make on any given day, would be to work out start times for each trip recorded as having used them, then check this against records for household individuals to try to work out who used which household vehicle first in the day so which stage was the car's first. A similar problem would arise for establishing last use of the vehicle.

It would be an extremely time-consuming task to attempt this so an alternative method was sought. As it happens there is a variable that identifies the number of stages belonging to each trip: 'J23 - Number of Stages (including short walks)', whose criteria are shown in Table A2-2.

Table A2-2: List of criteria values for variable 'J23 – Number of stages (including short walks)'.

Criteria value	Banding
0	One
1	Two
2	Three
3	Four
4	Five
5	Six
6	Seven or more
999	Multipunched
999	No answers

So, two new Access files were created named 'TBA3aPHEV_j23_singleS' and 'TBA3bBEV_j23_singleS' that would use this variable to find and remove vehicles that had and journeys where their use was not the sole stage of the journey. Imported into each respectively were the results from the previous step listing vehicles for each that had no missing to or from home time data – 'TBA2_PHEVrecords_fulltimes' and 'TBA2_BEVrecords_fulltimes'.

A query was then run for both PHEV and BEV eligible vehicles to find vehicles with journeys that consisted of more than one stage, i.e. a value of ">0" for J23. A duplicates query was then used to list the vehicles those journeys belonged to, then an unmatched query used to select records belonging to vehicles other than those listed with journeys consisting of more than one stage.

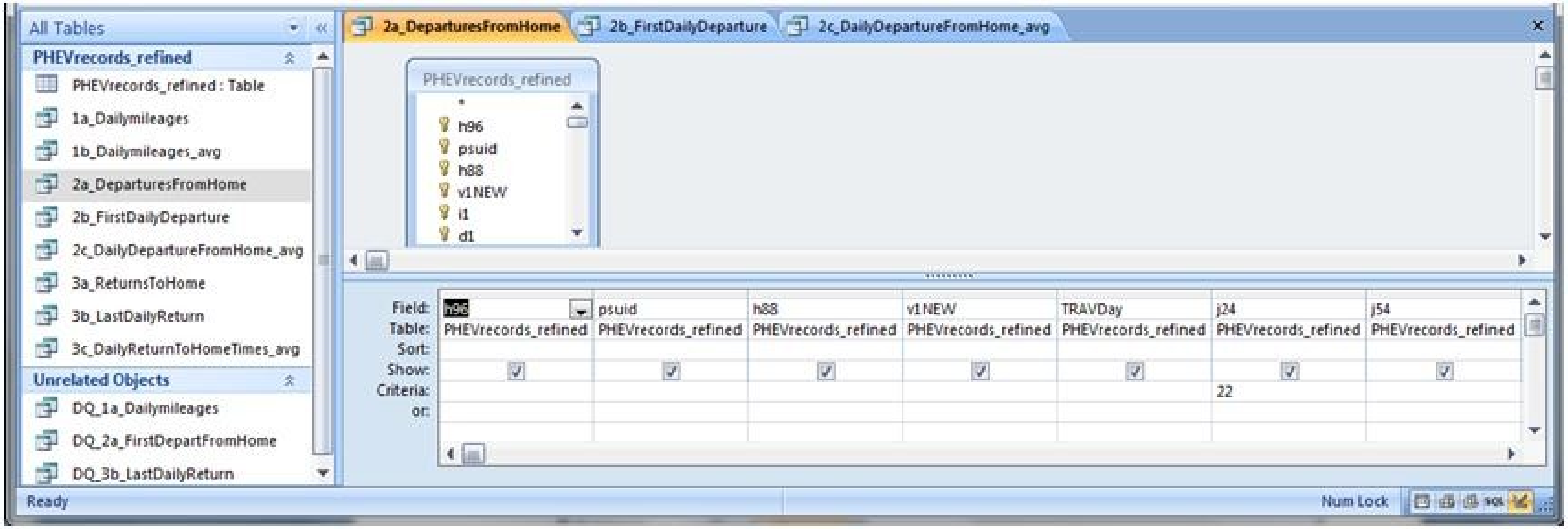
462 PHEV and 1823 BEV eligible vehicles had records for journeys consisting of more than one stage and these were distributed between 457 and 1723 households respectively. This left 2550 PHEV and 14591 BEV eligible vehicles that could be used to find average first departure from and last return to home times, distributed between 2410 and 10781 households respectively. Records for PHEV and BEV eligible vehicles whose stages were the sole stage of any journey they made were then exported into tab-delimited text files named 'TBA3aPHEVrec_fullt_singleS' and 'TBA3bBEVrec_fullt_singleS'.

CALCULATE AVERAGE FIRST DEPARTURE FROM AND AVERAGE LAST RETURN TO 'HOME' TIMES

Two new Access files were opened to establish average 'departure from' and average 'return to' home times for PHEV and BEV eligible vehicles, named 'TBA4a_PHEV' and 'TBA4b_BEV' respectively. Into 'TBA4a_PHEV' were imported the records for PHEV eligible vehicles with journey purpose from home start times and journey purpose to home end times, all of whose stages were the sole stages of journeys made by those vehicles – 'TBA3aPHEVrec_fullt_singleS'. The same import was made for 'TBA4b_BEV' but for the equivalent BEV eligible vehicles records: 'TBA3bBEVrec_fullt_singleS'.

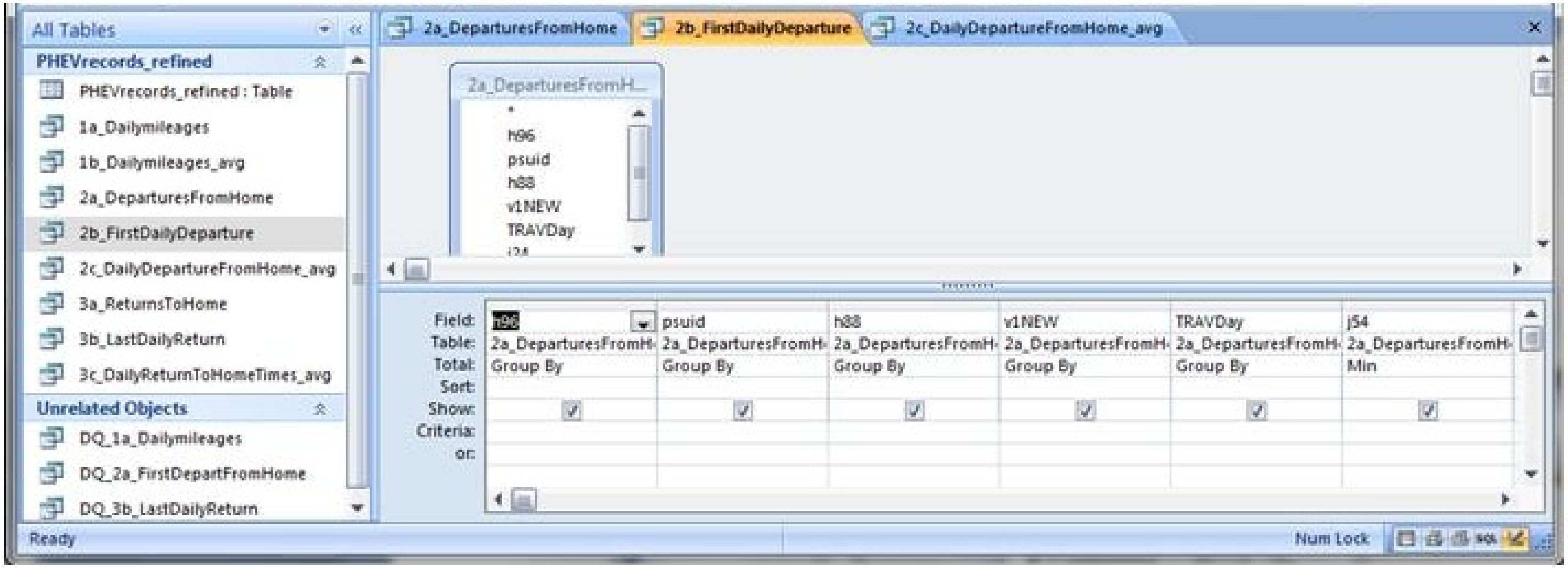
Queries were then run to establish 'first departures from' and 'last return to' home times for each vehicle for each day of the week, then additional queries to determine from those results averages for each (see Fig. A2.4 to Fig. A2.6 for an overview of the queries made for PHEV eligible vehicles).

Results are reported in Part 3 of the NTS statistics extraction method of Chapter 6. First departure times for both PHEV and BEV eligible vehicles were notably later on weekend days (Saturday and Sunday). PHEV tended to depart a little earlier on each day than BEV eligible vehicles. Return times for PHEV were later on every day compared with BEV, but both BEV and PHEV eligible vehicles had later return times on workdays than on weekend days Saturday and Sunday. SD for time data for both PHEV and BEV eligible vehicles were of the order of around 3 h for departure times and around 3-4 h for returns which tended towards 3 h on workdays and 4 h on weekends. This indicates that both average departure and return times have a lot of variation but that return times tend vary more on weekends than on workdays.



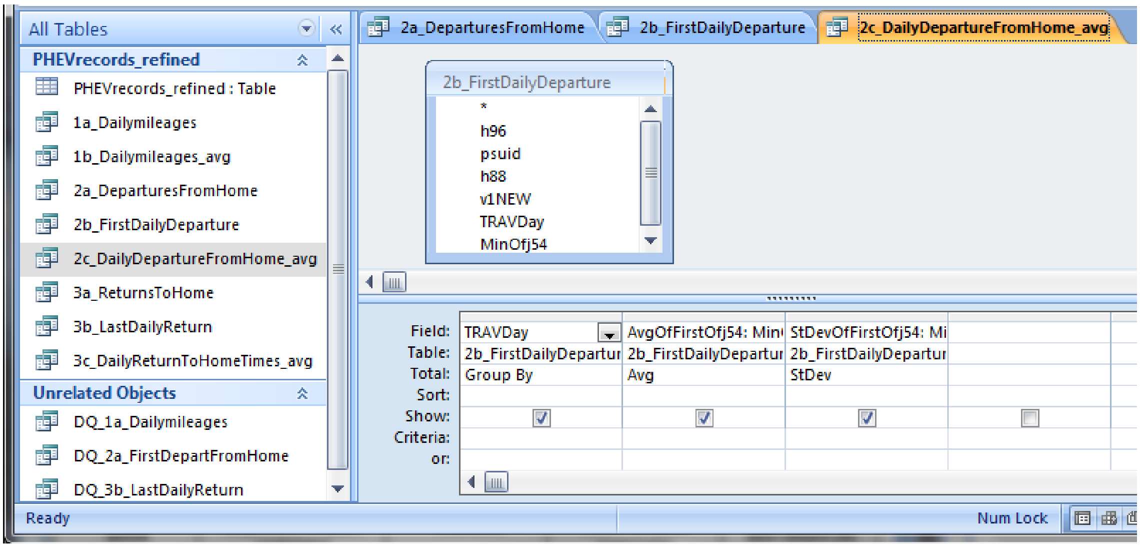
Field:	h96	psuid	h88	v1NEW	TRAVDay	j24	j54
Table:	PHEVrecords_refined	PHEVrecords_refined	PHEVrecords_refined	PHEVrecords_refined	PHEVrecords_refined	PHEVrecords_refined	PHEVrecords_refined
Sort:							
Show:	☑	☑	☑	☑	☑	☑	☑
Criteria:						22	
or:							

Fig. A2.4. Example query run to select records for journey start times (variable ‘j54’) from home (where variable ‘j24’ fulfils the criteria ‘=22’).



Field:	h96	psuid	h88	v1NEW	TRAVDay	j54
Table:	2a_DeparturesFromH	2a_DeparturesFromH	2a_DeparturesFromH	2a_DeparturesFromH	2a_DeparturesFromH	2a_DeparturesFromH
Total:	Group By	Group By	Group By	Group By	Group By	Min
Sort:						
Show:	☑	☑	☑	☑	☑	☑
Criteria:						
or:						

Fig. A2.5. Example query run to select from the results of the previous query in Fig. 6.20, the earliest departures (assumed to be first) on each day of the week.



Field:	TRAVDay	AvgOfFirstOfj54: Min	StDevOfFirstOfj54: Mi	
Table:	2b_FirstDailyDepartur	2b_FirstDailyDepartur	2b_FirstDailyDepartur	
Total:	Group By	Avg	StDev	
Sort:				
Show:	☑	☑	☑	☐
Criteria:				
or:				

Fig. A2.6. Query run from the results of the previous query in Fig. 6.21 in order to calculate mean average and SD of times for first departures from home.

IMPACT OF SELECTING VEHICLES WITH APPROPRIATE TIME DATA

As noted in Chapter 6, it was decided not to use the narrowed sample for assessing departure and return times, for the calculation of daily mileage statistics as the presence or absence of time information should not have any bearing on the reporting of distance travelled (instead it is likely primarily down to human error). But had both times and mileages been drawn from the same sample, average, SD and maximum mileage would have changed slightly. Table A2-3 and Table A2-4 that demonstrate how mileage figures would have changed, influenced by the removal of vehicles with missing time data and the removal of vehicles that had stages that were part of journeys that involved multiple stages.

Table A2-3: Difference made to Average, SD and Maximum mileage per day of the working week for vehicles eligible for replacement with PHEV by narrowing sample size (differences plus or minus to earlier result).

Day of the week	Average mileage (mi)	SD of mileage (mi)	Maximum mileage travelled (mi)
Monday	+0.4	-0.1	0.0
Tuesday	0.0	-0.8	0.0
Wednesday	-0.2	-2.6	-42.0
Thursday	+1.2	+0.3	0.0
Friday	-0.3	-1.3	0.0
Saturday	+0.5	+0.7	-30.0
Sunday	+0.7	-0.3	0.0

Table A2-4: Difference made to Average, SD and Maximum mileage per day of the working week for vehicles eligible for replacement with BEV by narrowing sample size (differences plus or minus to earlier result).

Day of the week	Average mileage (mi)	SD of mileage (mi)	Maximum mileage travelled (mi)
Monday	0.0	0.0	0.0
Tuesday	-0.1	0.0	0.0
Wednesday	+0.1	+0.1	0.0
Thursday	0.0	0.0	0.0
Friday	-0.1	-0.1	0.0
Saturday	-0.4	-0.2	0.0
Sunday	-0.3	-0.2	-0.6

MAKING SCATTER GRAPHS

To show the variation in daily mileages and times for first departures from and last returns to home in graphical form, an additional Access file was created to match up vehicles that had values for every day of the week for all three characteristics:

- mileage,
- time of first departure from home and
- time of last return to home.

This extra step was necessary because whilst every vehicle had a daily mileage, not every vehicle had records for both first departure from and last return to home times on the same day. There could be various reasons for this e.g. the vehicle was involved in a holiday for which there was no recorded departure from home because it occurred prior to the beginning of the travel week. Query results that gathered together 'per day' and 'per vehicle' records for mileage, first departure from and last return to home times from the previous two Access files (named 'TBA4a_PHEV' and 'TBA4b_BEV') were exported into appropriately named tab-delimited text files for BEV and PHEV eligible vehicles:

- 'TBA4a_PHEVdailymileages'
- 'TBA4a_PHEV_DailyDtimes'
- 'TBA4a_PHEV_DailyRtimes'
- 'TBA4b_BEVdailymileages'
- 'TBA4b_BEV_DailyDtimes'
- 'TBA4b_BEV_DailyRtimes'

These tab-delimited files were then imported into two new Access files: PHEV eligible results into ‘TBA5a_PHEVcombined’ and BEV eligible results into ‘TBA5b_BEVcombined’. Within these files the tables of imported results were linked together through relationships (as exampled for PHEV eligible vehicles in Fig. A2.7) that connected up ‘H96 – Sample year’, ‘PSUID – PSU (Primary Sampling Unit) Identification Number’, ‘H88 – Household reference number’, ‘V1NEW - Vehicle Reference Number (corrected to match with ‘S22 – Whose vehicle?’)’ and ‘TRAVDay – Travel Day of the Week’.

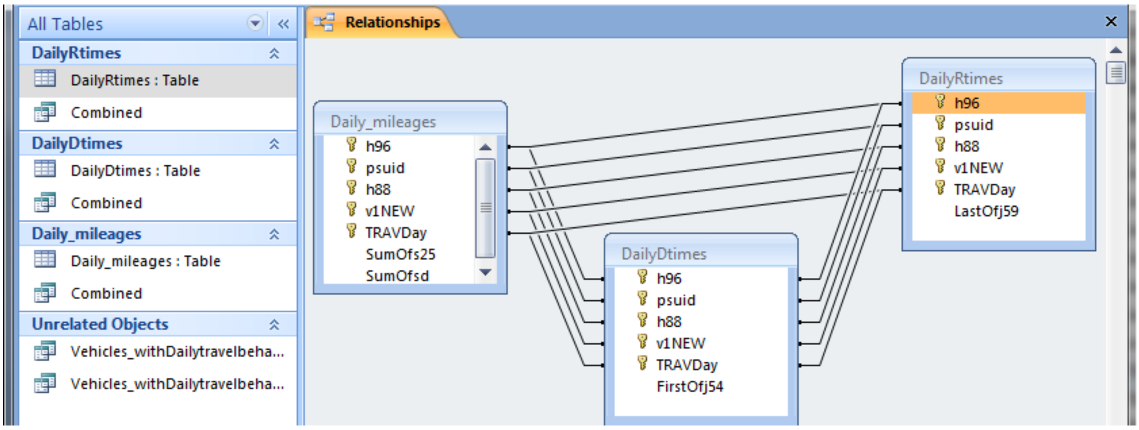
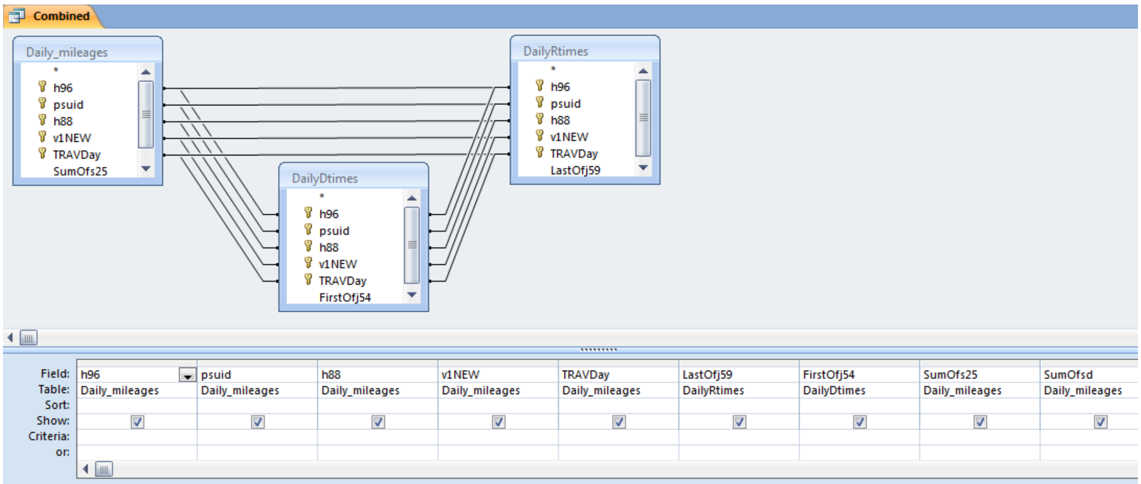


Fig. A2.7. Relationship links made between tables listing daily mileages (Daily_mileages), departure from home times (DailyDtimes) and return home times (DailyRtimes) per vehicle per day of the week.

Then a query was run to find records for PHEV and BEV eligible vehicles that matched up via these joins across all three tables (see Fig. A2.8 for the PHEV eligible vehicles example). In all, 2440 PHEV and 14377 BEV eligible vehicles were found to have complete matching records. These were distributed between 2307 and 10666 households respectively. The results of the queries were exported to tab-delimited text files named ‘TBA5a_PHEVdailyTraBeh’ and ‘TBA5b_BEVdailyTraBeh’ and subsequently imported into separate Excel files named ‘PHEVdisttimes’ and ‘BEVdisttimes’.

Once in Excel, records were sorted by day and daily mileage in miles (distances in tenths of miles as given in the NTS were converted into miles). Columns for departure and return times were left as ‘minutes past midnight’ because scatter graphs in Excel do not function with time values. Records were split into different tabs labelled for each day of the week. Mileage was put on a logarithmic scale. Scatter graph results are shown in part 3 of the NTS statistics extraction method in Chapter 6.



Field:	h96	psuid	h88	v1NEW	TRAVDay	LastOfj59	FirstOfj54	SumOfs25	SumOfsd
Table:	Daily_mileages	Daily_mileages	Daily_mileages	Daily_mileages	Daily_mileages	DailyRtimes	DailyDtimes	Daily_mileages	Daily_mileages
Sort:									
Show:	☑	☑	☑	☑	☑	☑	☑	☑	☑
Criteria:									
or:									

Fig. A2.8. Results of the above query will only contain records that have a matching combination of values for ‘h96’, ‘psuid’, ‘h88’, ‘v1new’ and ‘TRAVDay’, in other words: vehicles that for any given single day have matching records across all three tables for mileage, departure from home times and return home times.

Distances travelled affect departure and return times for all vehicles. The longer the distance, the more there is a tendency for the time between departure and return to elongate. The departure and return times on weekends vary more than on workdays, whilst on every day there is a period of time between midnight (0) and 06:00 h (360) of relative inactivity. Note that these results include points after midnight, occurring on the morning of the next day. It was not possible to split these records off and assign them to the next day in the time allowed for the project, so this needs to be taken into consideration when considering vehicle usage in the first few hours after midnight.

Weekends have a greater number of travel records than workdays and in the case of PHEV eligible vehicles, weekends seem to have a greater density of longer distance journeys than workdays. The return home times are slightly more variable than departure times so there seems to be tendency that if long distance travel is required, drivers are shifting their return home times in preference to departure from home times.

APPENDIX 3: MAKING SCENARIOS

This Appendix contains all additional information required for the construction of plug-in vehicle scenarios in Chapter 8 from the various information gathered together as part of the Parry Tool. Three scenarios were produced, each with two variations, additional details for which are listed here.

General points to note: the electricity demand data acquired from National Grid [8] used for the test week is half-hourly. This meant the following modifications had to be made:

- Hourly recharging rates for BEV and PHEV had to be divided by two to convert them into half-hourly recharging rates
- Last return home times were rounded up or down to the nearest half-hour
- First departure from home times (used to define recharging windows in scenario 2) were rounded down to the nearest half-hour to mark the last half hour they might be expected to be found recharging
- Recharging load durations (where calculated to reflect mileage variation in 1B, 2B and scenario 3, where calculated to reflect partial recharging for load-shifting between workdays and weekends in scenario 3) had to be rounded to the nearest half-hour

In all scenarios linear relationships were assumed between battery depletion and mileage travelled, so battery SOC was assumed linearly equivalent to the number of miles a vehicle could be expected to be able to travel. In all scenarios linear relationships were assumed between recovery of SOC and recharging duration, so recharging rate was assumed constant over the duration of recharging.

In all scenarios PHEV were assumed to travel mileages greater than their AER on every day of the test week. This meant that in 1B, 2B and scenario 3 where mileage variation is considered, PHEV were ignored. It is assumed that even if PHEV followed the same mileage behaviour as the BEV in those scenarios (travelling average daily mileages, average plus SD mileages, or maximum recorded mileages per day of the test week), their batteries would be fully depleted and in need of a flat-to-full recharge on every day. All scenarios used the same population estimates for PHEV and BEV made in Chapter 6 and used specifications from the same example vehicles to calculate loads for each, also previously given in Chapter 6.

SCENARIO 1 – UNRESTRICTED RECHARGING

The first variation (1A) uses the information gathered by the Parry Tool to construct recharging loads for plug-in vehicles, set their recharge start timings and then apply those loads to the chosen test week. The second variation (1B) is identical, but additionally includes some basic mileage variation for the BEV population so as to gain insight into how that factor might influence the shape of recharging loads and subsequent total demand.

Recharging start times in scenario 1 were assumed to coincide with the time that vehicles last returned home on each day. For this purpose, average last return to home times (rounded up or down to the nearest half-hour), as established by the NTS statistics extraction method were used (see Table A3-1, compare to Table 6-3 in Chapter 6 for unrounded figures).

Table A3-1: Average last return to home times, rounded up or down to the nearest half-hour, for BEV and PHEV.

Day of the week	Average last return home times (rounded)	
	BEV (h past midnight)	PHEV (h past midnight)
Monday	17:30	18:00
Tuesday	17:30	18:00
Wednesday	17:30	18:00
Thursday	17:30	18:00
Friday	17:30	18:00
Saturday	16:30	17:00
Sunday	16:30	17:00

Recharging loads for BEV and PHEV were calculated for 1A by multiplying the hourly recharging rate specifications for each in Chapter 5 by the national estimates for vehicles eligible to be replaced with each, from the NTS statistics extraction method (Part 1) in Chapter 6. These were then divided in two to provide the load over half an hour so as to apply them to the half-hourly demand profile for existing demand over the test week acquired from [8] as follows.

The PHEV population size was estimated at 1501290 vehicles. Load construction specifications for the Vauxhall Ampera were assumed – 4 h flat to full recharge at 4 kW/h. The calculation was as follows:

$$1501290 \times 4 = 6005160 \text{ kW} \quad = 6005 \text{ MW per hour for 4 h}$$

$$= \frac{6005}{2} = 3002.5 \text{ per half hour for 4 h}$$

The BEV population size was estimated at 8027332 vehicles. Load construction specifications for the Nissan Leaf were assumed – 10 h flat to full recharge at 2.4 kW/h. The calculation was as follows:

$$8027332 \times 2.4 = 19265597 \quad = 19266 \text{ MW per hour for 4 h}$$

$$= \frac{19266}{2} = 9633 \text{ MW per half hour for 4 h}$$

In 3B the BEV population is assumed to have some limited variation in the mileages travelled per day and therefore the duration of recharging required. 50% were assumed to travel the average mileage for each day of the week, 40% were assumed to travel the average plus the SD for each day of the week, 10% were assumed to travel the maximum mileage recorded for each day of the week.

Here, specifications gathered together for the example BEV (Nissan Leaf) in Chapter 5 were used again, specifically mileage range (109 miles) and battery capacity (24 kWh). It was unrealistically assumed for the BEV that battery capacity and mileage range were directly representative of each other[23]. This allowed proportional calculations could be made for the different recharging durations required to recover battery SOC to full.

The calculation of mileage travelled divided by the maximum mileage range of the BEV (109 miles) was assumed to proportionally represent depletion of battery SOC. So for example, if a vehicle travelled 21.8 miles:

$$\frac{21.8}{109} \times 100 = 20.0\ \% = \text{percentage of battery used} = \text{depletion of SOC}$$

$$\frac{20.8}{100} \times 24\ kWh = 4.8\ kWh \text{ of energy used}$$

Furthermore continuing the direct relationship assumed for SOC relative to recharging duration and rate, the duration could be calculated by dividing the number of hours taken for a flat-to-full recharge by the proportion of the battery assumed used:

$$\frac{20.0}{100} \times 10.0\ h = 2.0 \text{ h recharging duration required to recover batter to full SOC}$$

Recharging durations were thus calculated and were rounded up or down to the nearest half hour. See Table A3-2 to Table A3-4 to for the new recharging durations for these three subgroups based on their new daily mileages over the test week.

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[23] Realistic assumptions were hard to base upon literature available but as the project was never meant to be an exercise about results but instead one about how to get them, simple assumptions were made.

Table A3-2: 50% of BEV population travel average daily mileages (Scenario 1B).

Day of week	Mileage (mi) [1]	Energy usage (kWh)	Recharge duration (h) [2]
Monday	21.8	4.8	2.0 (2.0)
Tuesday	22.1	4.9	2.0 (2.0)
Wednesday	22.6	5.0	2.1 (2.0)
Thursday	22.6	5.0	2.1 (2.0)
Friday	22.9	5.0	2.1 (2.0)
Saturday	21.5	4.7	2.0 (2.0)
Sunday	20.7	4.5	1.9 (2.0)

[1] Mileage is the average mileage travelled on each day by vehicles classified as potential BEV in Chapter 6.

[2] Recharge duration is rounded to the nearest half hour in brackets, the rounded value is used in subsequent calculations.

Table A3-3: 40% of BEV population travel average plus SD daily mileages (Scenario 1B).

Day of week	Mileage (mi) [1]	Energy usage (kWh)	Recharge duration (h) [2]
Monday	40.6	8.9	3.7 (3.5)
Tuesday	40.9	9.0	3.8 (4.0)
Wednesday	41.7	9.2	3.8 (4.0)
Thursday	41.5	9.1	3.8 (4.0)
Friday	42.4	9.3	3.9 (4.0)
Saturday	41.4	9.1	3.8 (4.0)
Sunday	40.9	9.0	3.7 (3.5)

[1] Mileage is the average mileage travelled on each day plus by vehicles classified as potential BEV in Chapter 6, plus the relevant SD mileage for each day.

[2] Recharge duration is rounded to the nearest half hour in brackets, the rounded value is used in subsequent calculations.

Table A3-4: 10% of BEV population travelling maximum daily mileages (Scenario 1B).

Day of week	Mileage (mi) *1	Energy usage (kWh)	Recharge duration (h) *2
Monday	100.5	22.1	9.2 (9.0)
Tuesday	100.5	22.1	9.2 (9.0)
Wednesday	100.0	22.0	9.2 (9.0)
Thursday	100.0	22.0	9.2 (9.0)
Friday	100.6	22.2	9.2 (9.0)
Saturday	100.4	22.1	9.2 (9.0)
Sunday	100.6	22.2	9.2 (9.0)

[*1] Mileage is the maximum mileage travelled on by any vehicle classified as potential BEV in Chapter 6.

[*2] Recharge duration is rounded to the nearest half hour in brackets, the rounded value is used in subsequent calculations.

SCENARIO 2 – RESTRICTED RECHARGING (RECHARGING REGMIES)

The first variation (2A) uses the information gathered by the Parry Tool inform the design of a recharging demand management strategy and time-block scheduling method. 2A is identical to 1A except that the BEV and PHEV populations have been split into groups that are scheduled to start recharging at different times to one another per day of the test week, making 2A comparable to 1A. The second variation (2B) is identical to 2A, but additionally includes some basic mileage variation for the BEV population, as was included in 1B, making 2B comparable to 1B. Adding to the descriptions given in Chapter 8, further information about the construction of Recharging Regimes is given here.

RECHARGING REGIME DESIGN STRATEGY (NOTES)

Recharging window timings and sizes for PHEV and BEV eligible vehicles were considered as part of the Recharging Regime design strategy. As before in scenario 1, last return home times were rounded up or down to the nearest half-hour, but first departure from home times were rounded down to the nearest half-hour to mark the last half hour that plug-in vehicles might be expected to be found recharging.

Table A3-5 lists the rounded average first departure from and last return to home times for PHEV eligible vehicles and the subsequent sizes of recharging windows per day of the week. Table A3-6 lists the rounded average first departure from and last return to home times for BEV eligible vehicles and the subsequent sizes of recharging windows per day of the week. Compare to Table 6-3 in Chapter 6 for unrounded figures.

Table A3-5: Rounded average first departure from and last return to home times and recharging window duration per day of the working week, for vehicles eligible for replacement with PHEV.

Day of the week	Rounded first departure times (h past midnight)	Rounded last return home times (h past midnight)	Recharge window duration (h)
Monday	09:00	18:00	15:00
Tuesday	09:00	18:00	15:00
Wednesday	09:00	18:00	15:00
Thursday	09:00	18:00	15:30
Friday	09:30	18:00	16:30
Saturday	10:30	17:00	18:30
Sunday	11:30	17:00	16:00

Table A3-6: Rounded average first departure from and last return to home times and recharging window duration per day of the working week, for vehicles eligible for replacement with BEV.

Day of the week	Rounded first departure times (h past midnight)	Rounded last return home times (h past midnight)	Recharge window duration (h)
Monday	09:30	17:30	15:30
Tuesday	09:00	17:30	15:30
Wednesday	09:00	17:30	16:00
Thursday	09:30	17:30	16:00
Friday	09:30	17:30	17:30
Saturday	11:00	16:30	19:00
Sunday	11:30	16:30	17:00

DETERMINING RECHARGING GROUPS AND TIMINGS (NOTES)

As noted in Chapter 8, there were four variations that progressed the design of recharging group sizes and timings prior to the final version. These are presented in more detail here.

V1 – Recharge vehicles to be ready for use as soon as possible

In this first version (V1), BEV groups are assumed to begin recharging at half-hourly intervals starting at 18:00 h. The calculation for the number of BEV in the first group, Alpha – $N_{B\alpha}$ – was as follows where C_R is the Redundant Capacity (arbitrary network limit minus existing demand) at 18:00 h in kW and r_B is the recharge rate of BEV in kW/h:

$$N_{B\alpha} = \frac{C_R}{r_B}$$

The second group of BEV, Beta – $N_{B\beta}$ – begins recharging half an hour later at 18:30 h. The calculation for the number of BEV in Beta group must include the subtraction of the recharging load of Alpha Group – who are assumed to already be recharging – from redundant capacity at 18:30 h:

$$N_{B\beta} = \frac{C_R - r_B N_{B\alpha}}{r_B}$$

The calculation expands for each additional group as the recharging load of previous groups is subtracted from the available redundant capacity. As such the number of vehicles in Gamma group – $N_{B\gamma}$ – was calculated as follows:

$$N_{B\gamma} = \frac{C_R - r_B\left(N_{B\alpha} + N_{B\beta}\right)}{r_B}$$

To calculate the number of vehicles in subsequent groups all that was required was to add into the brackets the number of vehicles calculated for each of the previous groups. Each time a number of vehicles for a group is calculated, the figure is rounded to the nearest whole. The process is continued until all BEV are allocated a group.

V1 proved that timing BEV groups too closely together near the existing demand peak results in the necessity for them to be split into more than six groups. 90.5% of BEV could be accommodated in the first 6 groups, leaving roughly 762,000 vehicles that would need to go into yet another group. If PHEV were lumped together into one group then that group could not begin recharging earlier than 21:30 h. If split into two groups of equal size, the size of loads for each group would still be too large to start any earlier.

Another criticism of V1 is that it relied on the maximum usage of redundant capacity when it is least available – during the normal peak hours of existing demand. The arbitrary network limit would be breached if additional vehicles were added especially to groups with earlier recharge start times.

V2 – Spread vehicles into fewer groups to simplify choice

If scheduling groups half an hour apart led to more than 6 groups, then it was reasoned Version 2 (V2) should test how many and what size groups would be required if scheduled to start recharging an hour apart. The same calculations from V1 were applied and the result was that all BEV could be accommodated by splitting them into only four groups (see Fig. A3.1).

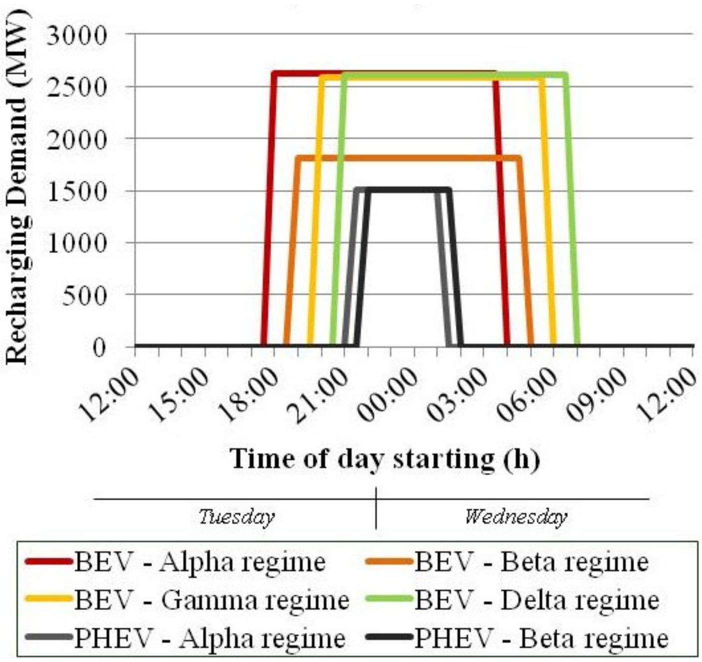


Fig. A3.1. Recharging groups for the four BEV groups and two PHEV groups established in the V2 of constructing recharging schedules for plug-in vehicles.

Again PHEV are constrained to begin recharging no earlier than 21:30 h when lumped together in one group, or when split into two groups of equal number. Like the V1, V2 still relies on the maximum usage of redundant capacity when redundant capacity is least available during the hours when existing electricity demand is at it its highest. As in V1, the arbitrary network limit will be breached if additional vehicles are added, particularly to groups with earlier recharge start times.

V3 – Allow spare redundant capacity at times of least availability, avoid infringement of next day's peaking period

There is a need to keep spare redundant capacity available as a contingency. Such contingency may be required were some vehicles to disobey their group's recharging instructions, or if additional vehicles join the population in future. Although this is largely subjective, a demonstrative small allowance has been made in V3. Thus it was decided that the number of BEV that could potentially begin recharging in each time slot should be halved.

This resulted in the necessary number of groups increasing from four to six to accommodate all BEV. The number of vehicles in each group was smaller, so each group contributed a smaller load. Compare A3.2 to A3.1 to see the difference this has made to scheduling.

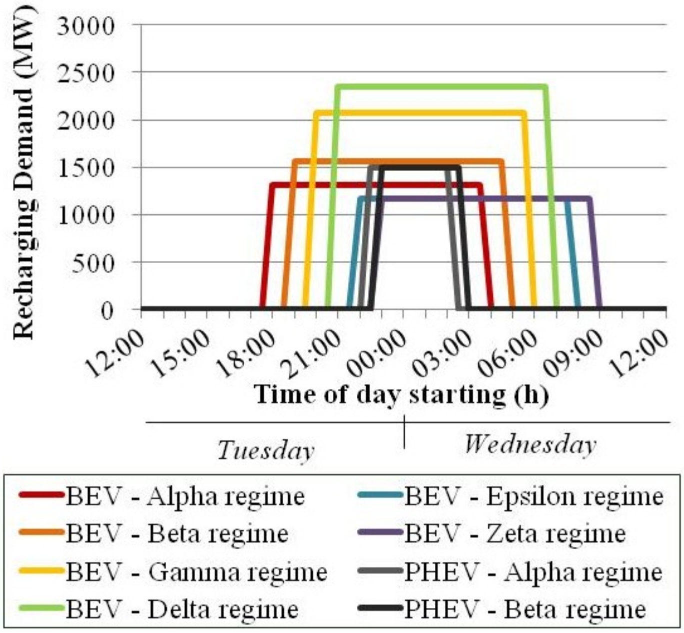


Fig. A3.2. In V3 at constructing recharging schedules BEV were split into six groups, PHEV into two, to better spread loads.

Fig. A3.3 shows that the load profile has improved, allowing spare redundant capacity closer to the peak and better advantage to be taken redundant capacity. Recharging windows for BEV and PHEV remain unbroken but a new problem now arises: the loads for the last two groups begin encroach on the start of the next day's peak period.

The last two groups to begin recharging are Epsilon and Zeta. Their scheduled recharge start times of 22:00 h and 23:00 h respectively. Flat-to-full recharging requires a recharge duration of 10 hours which puts the cessation of recharging the next day as being by 08:00 h for Epsilon group and by 09:00 h for Zeta group. It was reasoned thus that shifting the timing of these groups may reduce the necessity to add load to the next day's peak and may also help utilise redundant capacity when it is most available. Three alternatives were thus tested:

- Make Zeta group start recharging half an hour earlier.
- Make Epsilon and Zeta groups start recharging an hour earlier.
- Make Epsilon group start recharging half an hour earlier and make Zeta group start recharging an hour earlier.

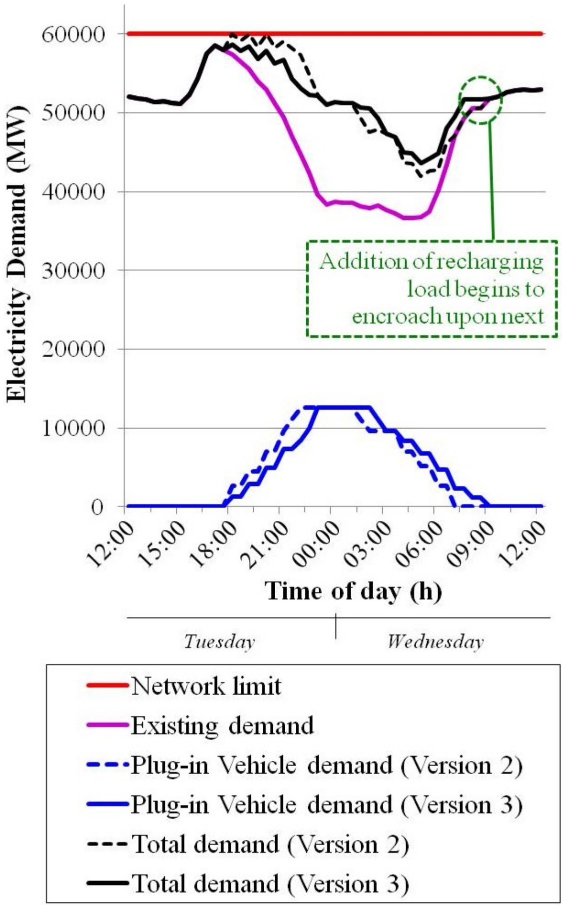


Fig. A3.3. Comparison of load profiles before and after BEV loads were spread wider from four groups in V2 to six groups in V3.

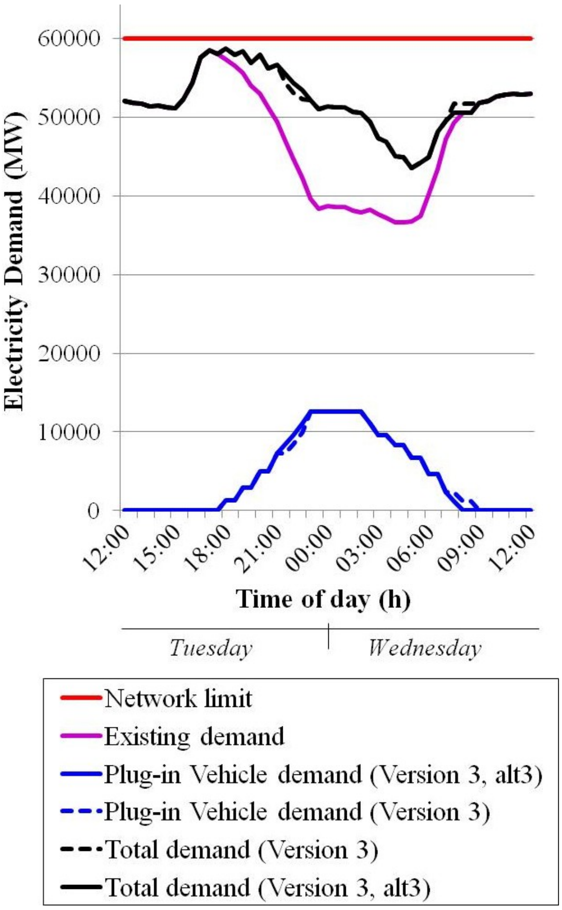


Fig. A3.4. Recharging loads for BEV groups Epsilon and Zeta were moved to compress overall plug-in vehicle load avoiding, infringement of the next day's peak in V3, alternative 3.

The third alternative proved best and the impact of bringing forward the recharging of both Epsilon and Zeta is shown in Fig. A3.4.

V4 – Focus recharging groups to better take advantage of redundant capacity at times of most availability

Spreading the vehicles into more groups improved the utilisation of redundant capacity. The shifting of later BEV group recharge start times has improved the situation further by affecting the shape of the recharging load curve to better match that of redundant capacity availability, but there is still room for improvement.

In V4 the percentage representation of vehicles in each BEV group was calculated and manually adjusted to make the groups that start recharging at the earliest times a little smaller in order to leave more redundant capacity for emergencies at the times when it is at its smallest.

See Table A3-7 for adjustments made. Note that figures for numbers of vehicles are rounded to the nearest whole vehicle. Fig. A3.5 shows the differences these modifications make to the overall demand profile.

Table A3-7: Manual adjustments made in V4 to numbers of vehicles per BEV groups established in V3.

BEV group	% of total BEV population (from V3)	Adjusted % of total (increase or decrease provided in brackets)		New number of vehicles per group
Alpha	13.62	7.00	(-6.62)	561913
Beta	16.20	13.00	(-3.20)	1043553
Gamma	21.53	22.00	(+0.47)	1766013
Delta	24.33	24.00	(-0.33)	1926560
Epsilon	12.16	22.00	(+9.84)	1766013
Zeta	12.16	12.00	(-0.16)	963280
Total	**100**	**100**	**(0.00)**	**8027332**

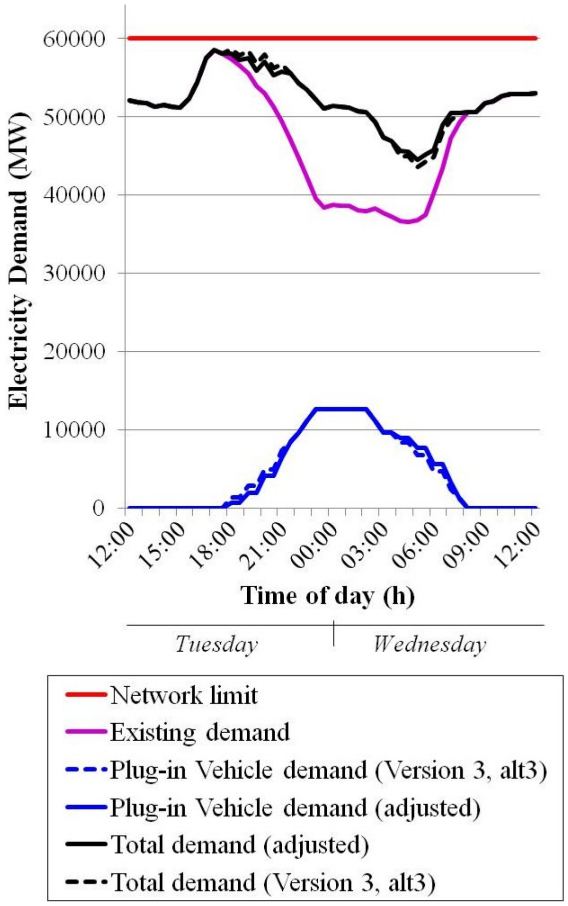


Fig. A3.5. BEV group sizes from V3 were adjusted in V4 to shave off a little of the load occurring close to existing peak demand and take better advantage of the lull.

Another opportunity to improve utilisation of redundant capacity would be to alter the timing of the two PHEV groups which contribute a load roughly the size of one of the BEV groups but for half the duration. To test this, the recharge timing for Alpha group was kept constant, whilst Beta group was scheduled to begin recharging later. Fig.A3.6 shows four of the possible alternative start times for the PHEV Beta group recharging load – 23:30 h, 00:30 h, 01:30 h and 02:30 h (numbered alt1 to alt4 respectively) – and demonstrates the impact of moving Beta group's recharging slot to these later times.

Scheduling the recharge start time of PHEV group Beta to start at 02:30 h – starting as PHEV Alpha group finishes – yielded the best result. Fig. A3.7 shows the impact on overall plug-in vehicle recharging load (compare against A3.5 for difference made) while Fig. A3.8 shows the new plug-in vehicle recharging schedule.

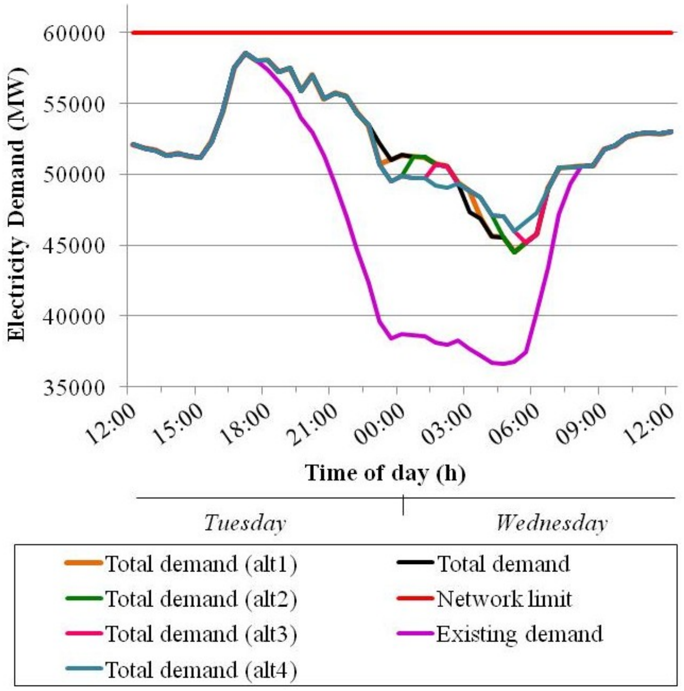


Fig. A3.6. Testing the impact upon the total demand profile when PHEV group Beta is allocated to four alternative time slots in Version 4.

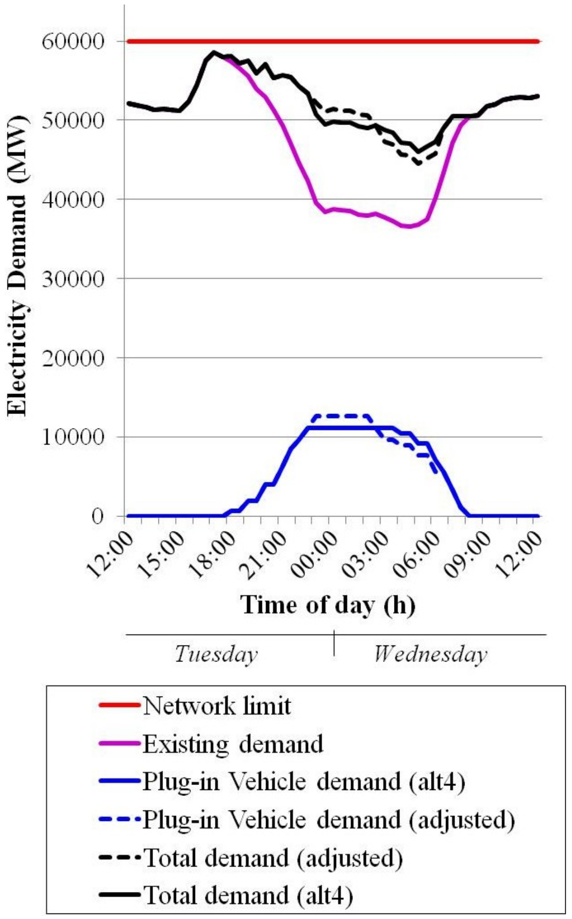


Fig. A3.7. Load profiles for V4, comparing before and after PHEV group Beta was moved to start recharging at 02:30 h.

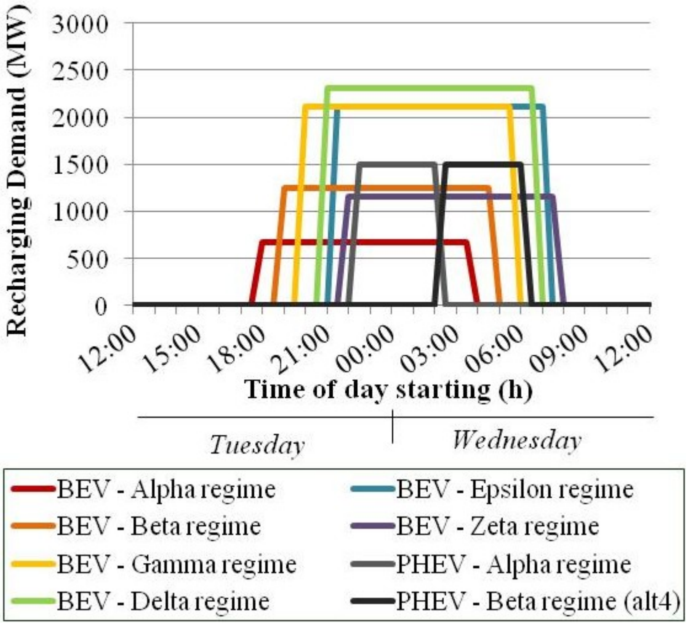


Fig. A3.8. Finalised recharging groups for BEV and PHEV from Version 4.

VF – Apply Recharging Regimes to plug-in vehicle loads over the test week

In the final version of Recharging Regimes, the groups and timings developed in V4 (already set to the day of highest demand in the test week, and the year from which the test week was taken) must be applied and modified according to the entire test week – Monday 5th to Sunday 11th January 2009. Initially this meant that the standard recharge timings established in V4 were applied to each day of the test week, but travel behaviour analysis in Chapter 6 showed that the average time of first departure from home is later on Saturday and Sunday, whilst the average last return home time is earlier on those days. This is the case for both BEV and PHEV and means therefore that Friday, Saturday and Sunday have longer recharge windows for vehicles so recharging loads on those nights can be spread out over more hours (see previous Table A3-5 and Table A3-6) .

Ideally recharge scheduling on Friday, Saturday and Sunday nights should be adjusted to improve the use of redundant capacity during lulls in existing demand in the early hours of Saturday and Sunday. Expansion of the recharging window to earlier hours is not as useful as expanding it to later hours because coincidence of recharging loads and existing peak demand should be avoided. Only Friday and Saturday have recharging windows that are also widened to later hours. Load spreading was therefore more feasible on these days. The existing peak in demand for the test week was a little earlier so Saturday's load was spread half an hour earlier as well as taking advantage of the expansion of the window to later hours (see Fig. A3.9).

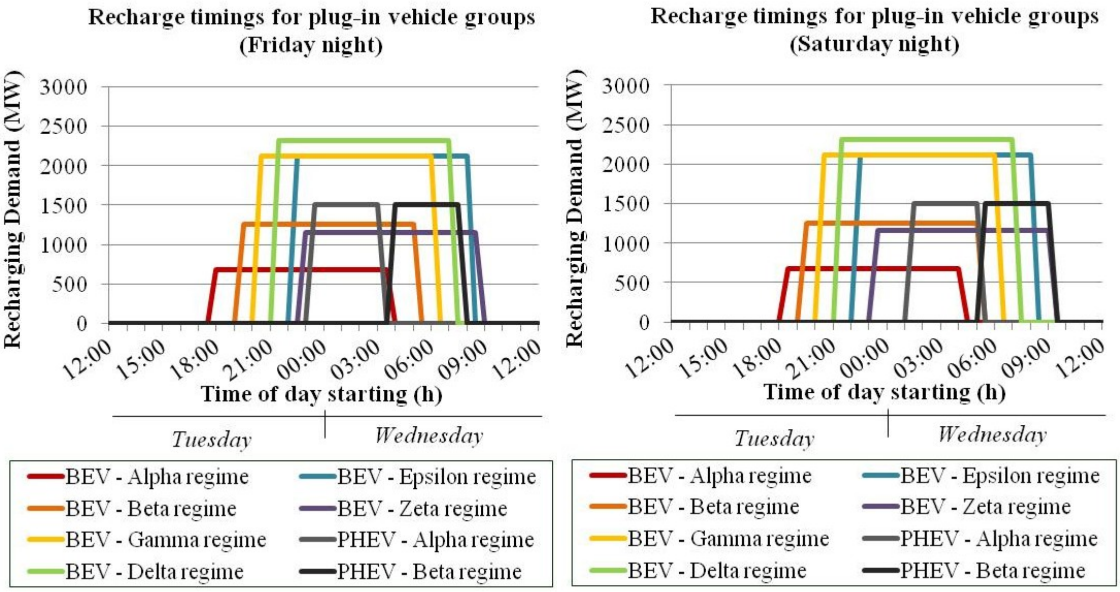


Fig. A3.9. Recharge scheduling for plug-in vehicles for Friday (left) and Saturday (right) has been altered to spread loads over the larger recharging windows assumed available on these days. Compare to Fig. A3.8 to compare difference to workdays.

Alterations to Sunday's load were prevented because the following day, Monday, is a week/work day – there was no expansion of the recharging window to later hours meanwhile spreading loads earlier would have added to the existing demand peak on that day. The alterations made to recharge scheduling for groups for Friday and Saturday in Fig. A3.9 can be compared to Fig. A3.8 in the previous subsection which shows the standard recharge scheduling for workdays. The change in the total load profile made by altering Friday and Saturday's recharging schedules can be seen in Fig. A3.10.

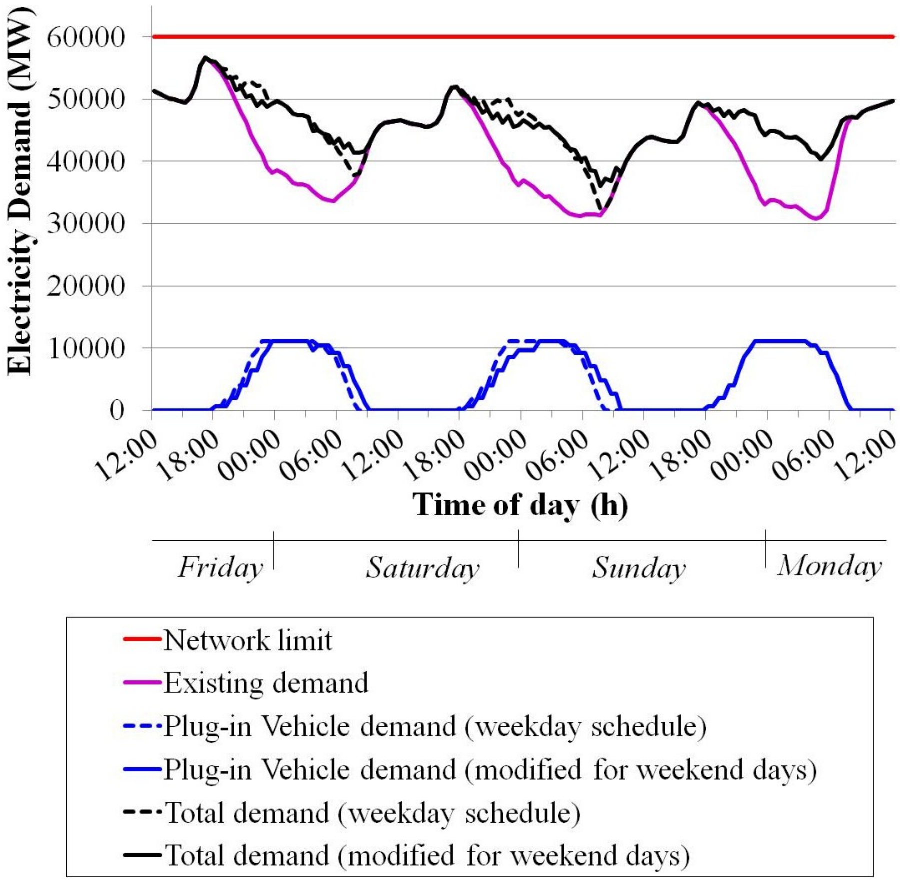


Fig. A3.10. Recharge schedules for plug-in vehicle groups starting on Friday and Saturday nights have been modified to spread recharging loads over the wider recharge windows available on these days. Sunday remains unchanged because although the recharge window for that day is also wider than for a workday it is only expanded to earlier hours and the timing of the existing demand peak prevented the spreading recharging loads in that direction.

This completes the construction of Recharging Regimes. Table 8.7 and 8.8 describe group sizes for BEV and PHEV as well as group designations for identification. Tables 8.9 and 8.10 show the assumed recharging start times for each group on each day of the test week.

Table A3-8: Final division of BEV into groups for the application of Recharging Regimes.

BEV group	New number of vehicles per group
Alpha	561913
Beta	1043553
Gamma	1766013
Delta	1926560
Epsilon	1766013
Zeta	963280
Total	**8027332**

Table A3-9: Final division of PHEV into groups for the application of Recharging Regimes.

PHEV group	New number of vehicles per group
Alpha	750645
Beta	750645
Total	**1501290**

Table A3-10: Recharging start times for BEV groups.

BEV group	Alpha	Beta	Gamma	Delta	Epsilon	Zeta
Day and start time	Mon 18:00	Mon 19:00	Mon 20:00	Mon 21:00	Mon 21:30	Mon 22:00
	Tue 18:00	Tue 19:00	Tue 20:00	Tue 21:00	Tue 21:30	Tue 22:00
	Wed 18:00	Wed 19:00	Wed 20:00	Wed 21:00	Wed 21:30	Wed 22:00
	Thu 18:00	Thu 19:00	Thu 20:00	Thu 21:00	Thu 21:30	Thu 22:00
	Fri 18:00	Fri 19:30	Fri 20:30	Fri 21:30	Fri 22:30	Fri 23: 00
	Sat 18:30	Sat 19:30	Sat 20:30	Sat 21:30	Sat 22:30	Sat 23:30
	Sun 18:00	Sun 19:00	Sun 20:00	Sun 21:00	Sun 21:30	Sun 22:00

Table A3-11: Recharging start times for PHEV groups per day of the test week.

PHEV group	Alpha	Beta
Day and start time	Mon 22:30	Tue 02:30
	Tue 22:30	Wed 02:30
	Wed 22:30	Thu 02:30
	Thu 22:30	Fri 02:30
	Fri 23:30	Sat 04:00
	Sun 01:30	Sun 05:30
	Sun 22:30	Mon 02:30

APPLYING MILEAGE VARIATION (2B)

2A uses the Recharging Regimes – group sizes and start times for recharging for BEV and PHEV – as described at the end of the last section, under the assumption that all vehicles require recharging from flat to full on every night of the test week. As the Recharging Regimes are designed on this worst case scenario – constructed based on the day of highest demand for the year first, then applied to the rest of the week and assuming flat-to-full recharging, there was no change to the recharging loads.

In 2B however, it is not assumed that every vehicle requires a flat-to-full recharge every night. 2B instead adopts the same basic mileage variation employed in 1B, meaning that PHEV continue to require flat-to-full recharging, but the BEV population is broken down such that 50% are assumed to be travelling the average mileage for each day, 40% the average plus the SD for each day, whilst 10% travel the maximum mileage recorded for each day, as based on the travel behaviour statistics gathered from the NTS [1] from the NTS statistics extraction method (Part 2) in Chapter 6. It was assumed that all BEV recharging groups were proportionally representative of the whole BEV population, so the same population break down of 50-40-10 would apply to each of them. As such, Table A3-2, A3-3 and Table A3-4 used for 1B also describe the distances, energy usage and recharging durations for each BEV recharging group.

SCENARIO 3 – RESTRICTED RECHARGING (WORKDAY TO WEEKEND LOAD-SHIFTING)

Descriptions for 3A and 3B are given in Chapter 8. Additional information is given here for the preliminary testing done as part of the 'Design basics and preliminary testing' part of their construction. A step-by-step breakdown for the construction of basic load-shifting and use of conditional formatting for the purpose of making allowance for an emergency mileage reserve are also provided here with screenshots of work carried out.

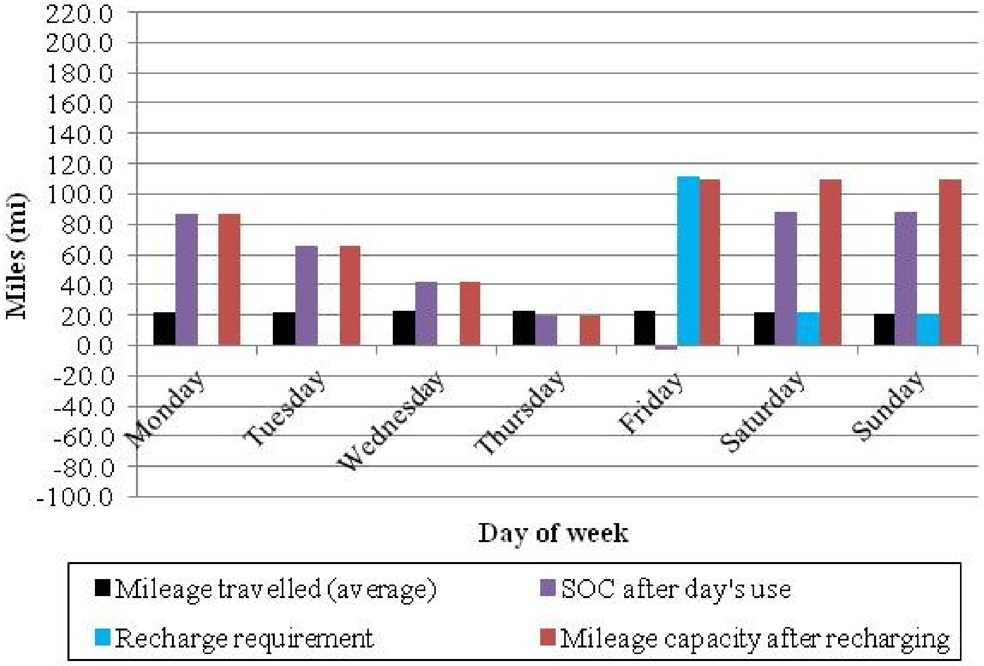
DESIGN BASICS AND PRELIMINARY TESTING

As noted in Chapter 8, the fact that some BEV (recharging subgroups *Ultimate* and *Extra* which are travelling average, and average plus SD mileages each day, respectively) means that these vehicles may not need full batteries to carry out their next day's driving. This allows for recharging loads to be shifted between different days if some vehicles do not recharge, or only partially recharge to attain SOC sufficient for the next day's activities.

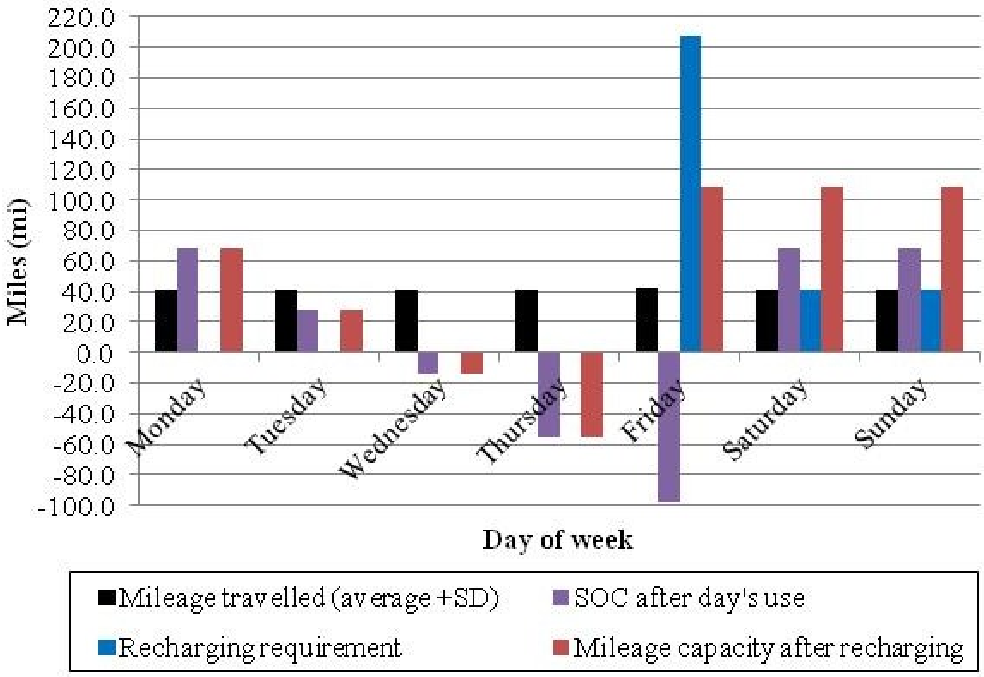
To compliment patterns in existing demand where electricity demand lulls over weekends compared to workdays, initially there were proposed two versions for recharging load-shifting. The first version (V1): weekend-only recharging for BEV. The second version (V2): partial recharging on workdays, recharging to full at weekends.

Ultimate and *Extra* subgroups were forbidden to recharge on workdays, but permitted to recharge to full SOC on Friday, Saturday and Sunday nights. For this exercise SOC was measured in equivalent miles, so 100% battery SOC would be equivalent to a SOC of 109 miles (as noted earlier under Scenario 1). Ideally for each day of the week the number of miles remaining in a vehicle's battery prior to travel should be equal to or more than the number of miles the vehicle is expected to travel.

Unfortunately, weekend-only recharging would be insufficient to meet the travel needs of drivers (see A3.11 and A3.12). Even if only making allowance for next day's expected mileage is considered, both *Ultimate* and *Extra* groups use more than their vehicle's entire battery capacity through travel use before they are recharged to full at the weekend.



A3.11. Weekend-only recharging for vehicles in *Ultimate* subgroups (the 50% of BEV assumed to be travelling average mileages for each day of the week and therefore with the least daily energy needs) proves problematic. On Friday, SOC after use falls below 0%. This means that by Friday there is insufficient SOC remaining to meet the travel needs of the driver.



A3.12. Weekend-only recharging for vehicles in *Extra* subgroups (the 40% of BEV assumed to be travelling average plus SD mileages for each day of the week) proves problematic. Note that from Wednesday to Thursday, SOC after use of vehicle during the day falls below 0%. This means that by Wednesday there is be insufficient SOC remaining to meet the travel needs of the driver.

This does not rule out the possibility that a selection of the BEV population could participate in weekend-only recharging. This is because as shown by Fig. 6.8 of Chapter 6, there is a great deal of variation for daily mileages travelled over the week by drivers. Regardless, it can at least be assumed that weekend-only recharging will not be appropriate for every BEV driver in that those travelling average daily mileages or more will be unable to adopt a weekend-only recharging pattern.

As V1 left vehicles with a SOC deficit, but V2 did not, V2 is the basic load-shifting that the next section starts with. Scenario 3A then evolves from V2 through the introduction of an allowance for an emergency mileage reserve. Scenario 3B evolves from 3A through the application of load levelling for recharging.

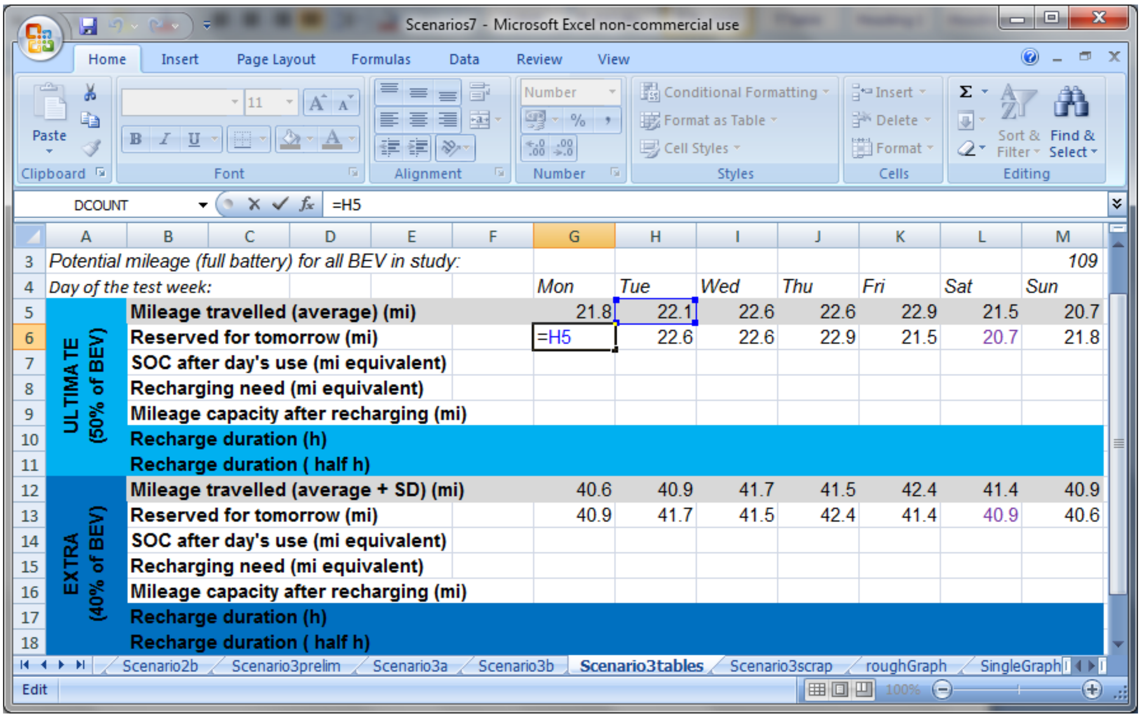
BASIC LOAD-SHIFTING PLUS EMERGENCY MILEAGE RESERVE (3A)

If restricting recharging only to weekends is not an option, could partial recharging BEV batteries during the week cover the necessity for vehicles to meet their next day's mileage, but still shift demand to weekends? What follows is a breakdown for how Excel tables were set up to do the necessary calculations to carry out load-shifting. Steps were identical for both *Ultimate* and *Extra* subgroups, so all steps apply and are shown as being applied to both in accompanying figures.

Step 1: What mileage will be required tomorrow?

The first step was to incorporate a calculation that worked out how many miles must be travelled the next day and therefore how many battery miles must be available after recharging (see A3.13).

At this stage, the required battery miles equals the number of miles the vehicle is expected to drive the next day, so for Monday, the battery miles that must be available is equal to cell H5, which contains the number of miles the vehicle will travel on Tuesday. For Sunday, the number of miles was assumed to be that for Monday's travel: cell G5.



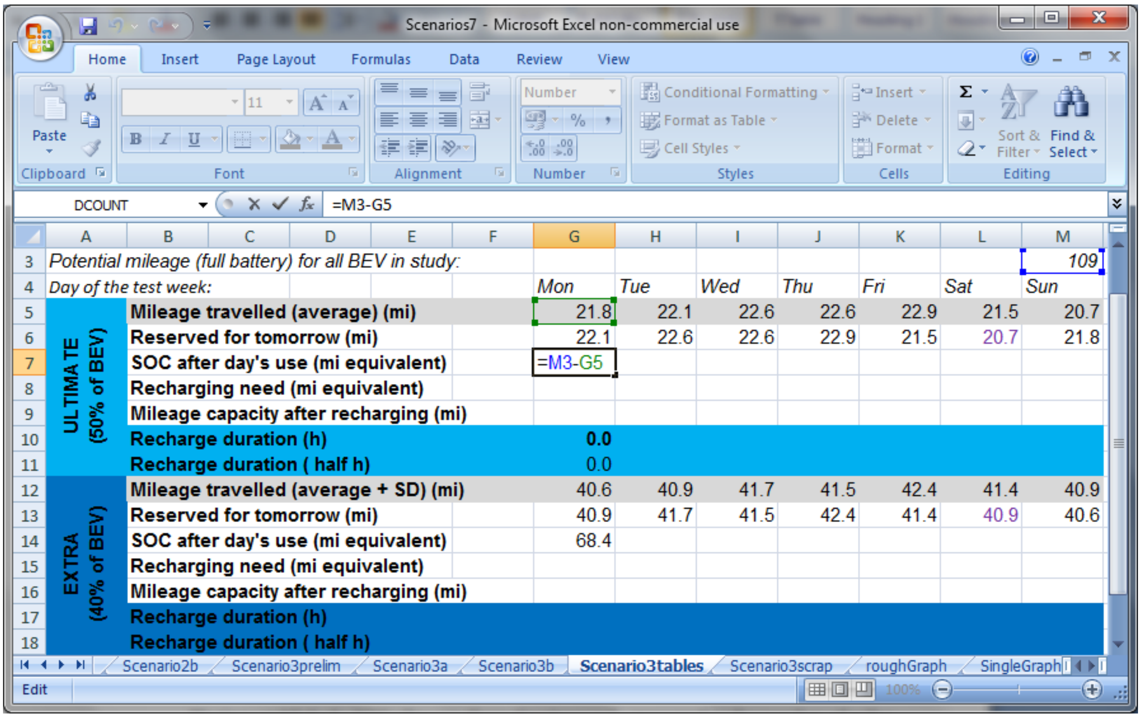
DCOUNT =H5

	A	B	G	H	I	J	K	L	M
3	*Potential mileage (full battery) for all BEV in study:*								*109*
4	*Day of the test week:*		*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*	*Sun*
5	**ULTIMATE (50% of BEV)**	**Mileage travelled (average) (mi)**	21.8	22.1	22.6	22.6	22.9	21.5	20.7
6		**Reserved for tomorrow (mi)**	=H5	22.6	22.6	22.9	21.5	20.7	21.8
7		**SOC after day's use (mi equivalent)**							
8		**Recharging need (mi equivalent)**							
9		**Mileage capacity after recharging (mi)**							
10		**Recharge duration (h)**							
11		**Recharge duration (half h)**							
12	**EXTRA (40% of BEV)**	**Mileage travelled (average + SD) (mi)**	40.6	40.9	41.7	41.5	42.4	41.4	40.9
13		**Reserved for tomorrow (mi)**	40.9	41.7	41.5	42.4	41.4	40.9	40.6
14		**SOC after day's use (mi equivalent)**							
15		**Recharging need (mi equivalent)**							
16		**Mileage capacity after recharging (mi)**							
17		**Recharge duration (h)**							
18		**Recharge duration (half h)**							

A3.13. Building a table in Microsoft Excel 2007 to determine partial recharging patterns for BEV subgroups *Ultimate* and "*Extra*". This screenshot shows the first step: establishing miles required for next day's driving.

Step 2: What is the SOC (battery miles equivalent) when vehicles come home on the first day of the test week?

The next step is to determine how many battery miles remain in the battery after each day's travel. Remember: in this study the relationship between battery capacity and potential mileage is assumed to be linear which may not hold true in reality. Here another assumption is made: vehicles start the week with a full battery SOC, (this is assumed to equate to 109 miles as noted earlier). So the first cell for Monday must be the number of miles available on a full battery – cell M3 – minus the number of miles travelled that day – cell G5 – as shown by A3.14.



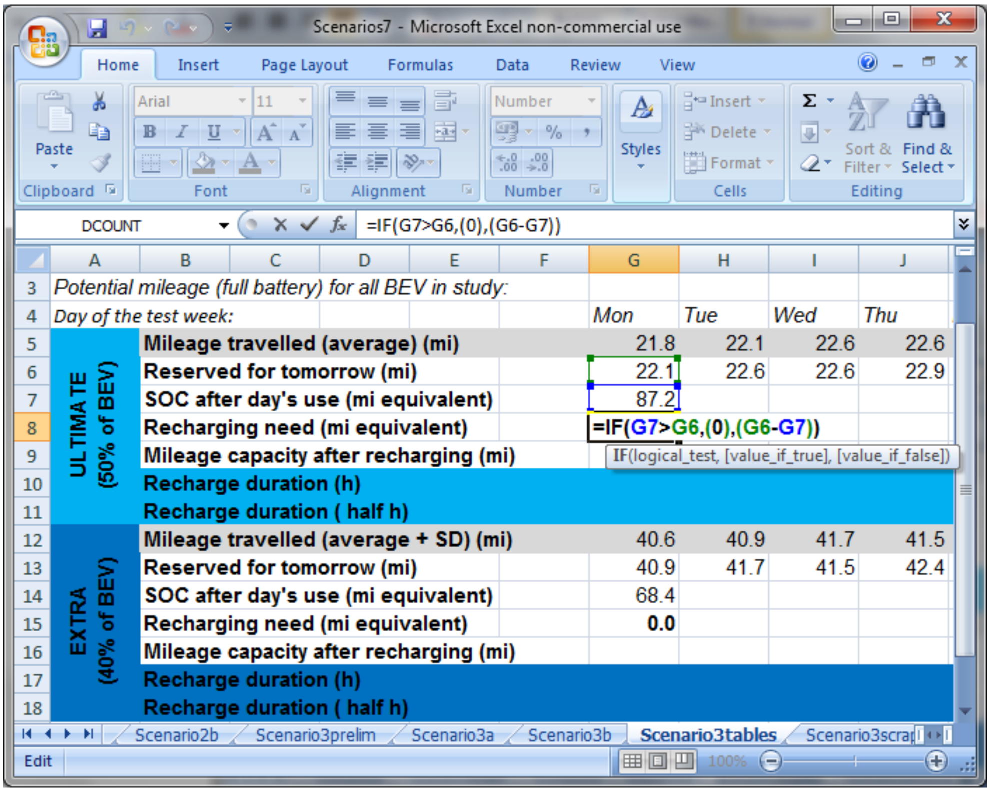
DCOUNT =M3-G5

	A	B–F	G	H	I	J	K	L	M
3	*Potential mileage (full battery) for all BEV in study:*								*109*
4	*Day of the test week:*		*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*	*Sun*
5	**ULTIMATE (50% of BEV)**	**Mileage travelled (average) (mi)**	21.8	22.1	22.6	22.6	22.9	21.5	20.7
6		**Reserved for tomorrow (mi)**	22.1	22.6	22.6	22.9	21.5	20.7	21.8
7		**SOC after day's use (mi equivalent)**	=M3-G5						
8		**Recharging need (mi equivalent)**							
9		**Mileage capacity after recharging (mi)**							
10		**Recharge duration (h)**	**0.0**						
11		**Recharge duration (half h)**	0.0						
12	**EXTRA (40% of BEV)**	**Mileage travelled (average + SD) (mi)**	40.6	40.9	41.7	41.5	42.4	41.4	40.9
13		**Reserved for tomorrow (mi)**	40.9	41.7	41.5	42.4	41.4	40.9	40.6
14		**SOC after day's use (mi equivalent)**	68.4						
15		**Recharging need (mi equivalent)**							
16		**Mileage capacity after recharging (mi)**							
17		**Recharge duration (h)**							
18		**Recharge duration (half h)**							

A3.14. Determining the number of miles left remaining in the vehicle battery after driving on each day of the week. Note that the unrealistic assumption is made here that there is a linear relationship between battery SOC and potential miles travel for vehicles.

Step 3: What is the recharging need for the first day of the test week?

Having established a SOC after use, the recharging need – measured as the number of miles that must be recovered to the battery – is calculated with an ‘IF’ formula as shown in A3.15. For example if it is true that the number of miles remaining in the battery after that day’s use – cell G7 – is greater than the number of miles required to be travelled tomorrow – cell G6 – then the value returned is zero. In other words: there is no need for recharging. If that statement is false, then the value that must be returned as the recharging need will be the number of miles required to be travelled tomorrow – cell G6 – minus the number of miles remaining in the battery after the day’s use – cell G7.



DCOUNT =IF(G7>G6,(0),(G6-G7))

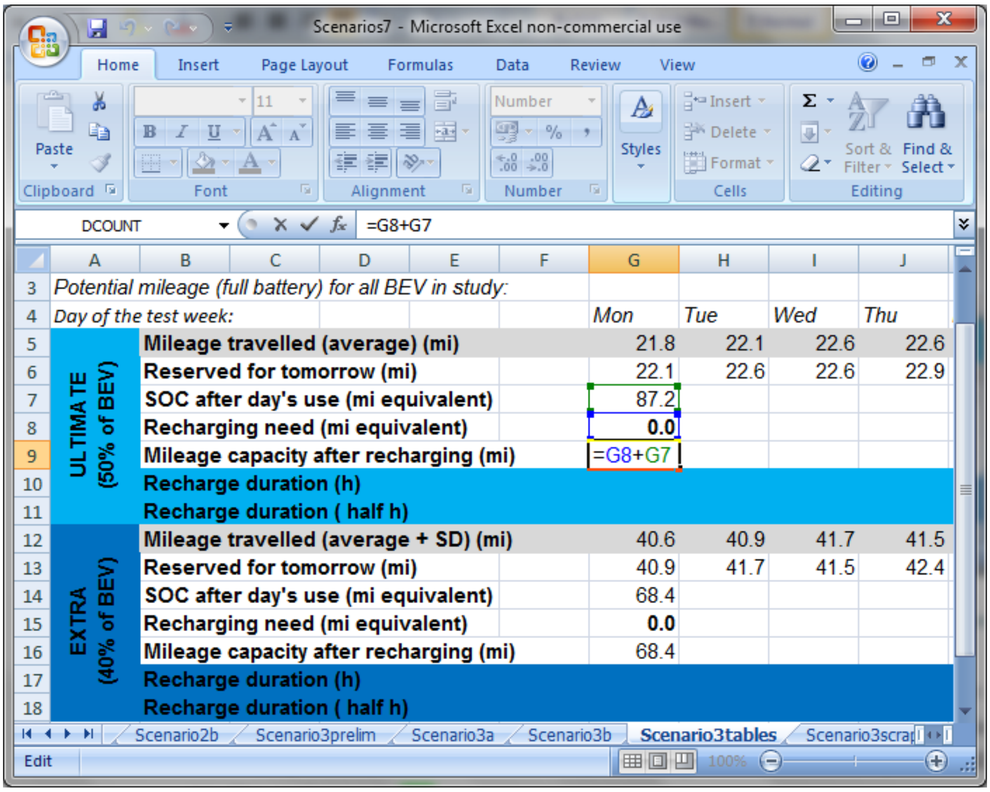
	A	B	C	D	E	F	G	H	I	J
3	*Potential mileage (full battery) for all BEV in study:*									
4	*Day of the test week:*						*Mon*	*Tue*	*Wed*	*Thu*
5	**ULTIMA TE (50% of BEV)**	**Mileage travelled (average) (mi)**					21.8	22.1	22.6	22.6
6		**Reserved for tomorrow (mi)**					22.1	22.6	22.6	22.9
7		**SOC after day's use (mi equivalent)**					87.2			
8		**Recharging need (mi equivalent)**					=IF(G7>G6,(0),(G6-G7))			
9		**Mileage capacity after recharging (mi)**								
10		**Recharge duration (h)**								
11		**Recharge duration (half h)**								
12	**EXTRA (40% of BEV)**	**Mileage travelled (average + SD) (mi)**					40.6	40.9	41.7	41.5
13		**Reserved for tomorrow (mi)**					40.9	41.7	41.5	42.4
14		**SOC after day's use (mi equivalent)**					68.4			
15		**Recharging need (mi equivalent)**					**0.0**			
16		**Mileage capacity after recharging (mi)**								
17		**Recharge duration (h)**								
18		**Recharge duration (half h)**								

IF(logical_test, [value_if_true], [value_if_false])

A3.15. Calculating recharging need based on the number of potential miles that must be recovered to the vehicle's battery in order to meet next day's driving needs.

Step 4: Calculate the mileage capacity assumed after recharging has taken place on the first day of the test week

The mileage capacity after recharging will be the same calculation for every cell in that row: the number of miles remaining in the battery at the end of the day – in the case of Monday this is cell G7 – plus the number of miles returned by recharging – in the case of Monday this is cell G8. This can be seen in A3.16.



DCOUNT =G8+G7

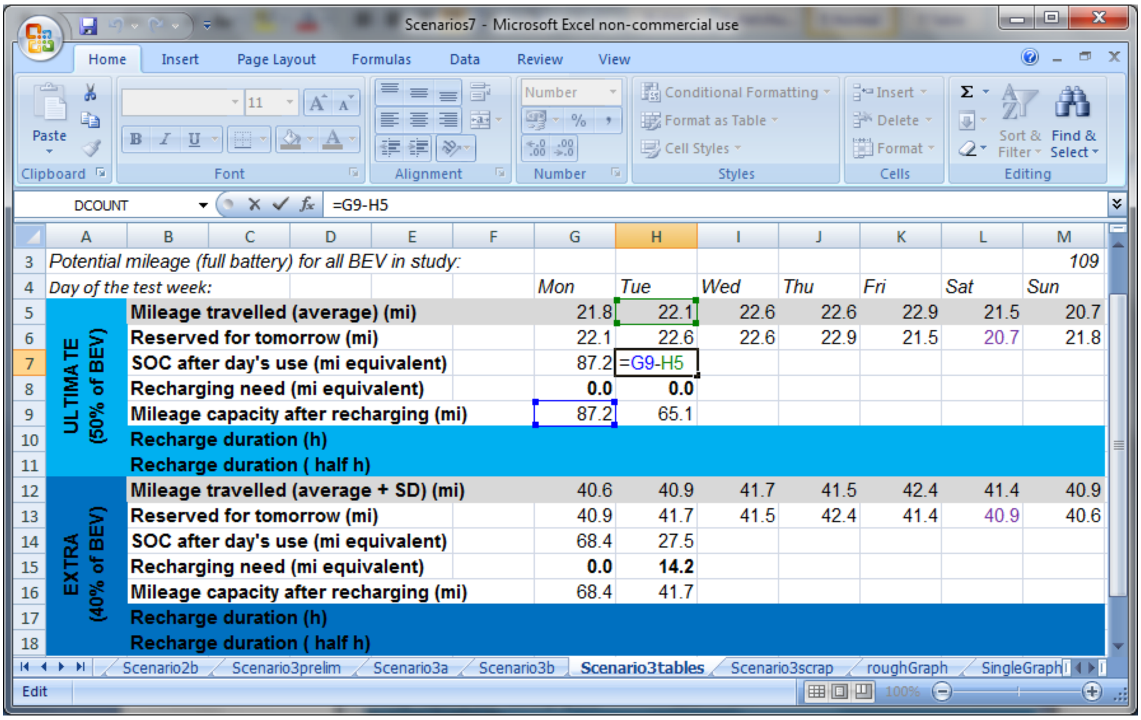
	A	B	C	D	E	F	G	H	I	J
3	*Potential mileage (full battery) for all BEV in study:*									
4	*Day of the test week:*						*Mon*	*Tue*	*Wed*	*Thu*
5	**ULTIMA TE (50% of BEV)**	**Mileage travelled (average) (mi)**					21.8	22.1	22.6	22.6
6		**Reserved for tomorrow (mi)**					22.1	22.6	22.6	22.9
7		**SOC after day's use (mi equivalent)**					87.2			
8		**Recharging need (mi equivalent)**					**0.0**			
9		**Mileage capacity after recharging (mi)**					=G8+G7			
10		**Recharge duration (h)**								
11		**Recharge duration (half h)**								
12	**EXTRA (40% of BEV)**	**Mileage travelled (average + SD) (mi)**					40.6	40.9	41.7	41.5
13		**Reserved for tomorrow (mi)**					40.9	41.7	41.5	42.4
14		**SOC after day's use (mi equivalent)**					68.4			
15		**Recharging need (mi equivalent)**					**0.0**			
16		**Mileage capacity after recharging (mi)**					68.4			
17		**Recharge duration (h)**								
18		**Recharge duration (half h)**								

A3.16. Calculating post recharge potential mileage remaining in vehicle battery.

Step 5: Copy formulae constructed so far for Monday to every day of the test week, then modify formulae for weekends

Copy first Monday's cells to Tuesday's column and edit the SOC after day's use cell for Tuesday to incorporate Monday's mileage capacity after recharging. So as shown in A3.17, the SOC after day's use for Tuesday – cell H7 – is equal to Monday's mileage capacity after recharging – cell G9 – minus Tuesday's mileage travelled – cell H5. Tuesday's cells from row 7 to row 9 can now be copied across to remaining days. Having done this however, columns for weekend days require modification. Note that Excel at this point may highlight a circular reference – this will be dealt with shortly.

A preferred day must be chosen to ensure batteries fully recover their SOC prior to the start of the next working week. Friday's evening peak in existing demand is higher than that of Saturday or Sunday's. Ideally if a specific day of the weekend were to be targeted to take the largest recharging load, it would be Saturday. Also the end of Sunday's recharging load is at greater risk of encroaching upon the start of Monday evening's peak. This needs to be avoided because, as noted from the analysis of national electricity demand data from National Grid [8] in Chapter 7, annual peak demand has been known to occur on Mondays in the past. Saturday therefore offers the best compromise.



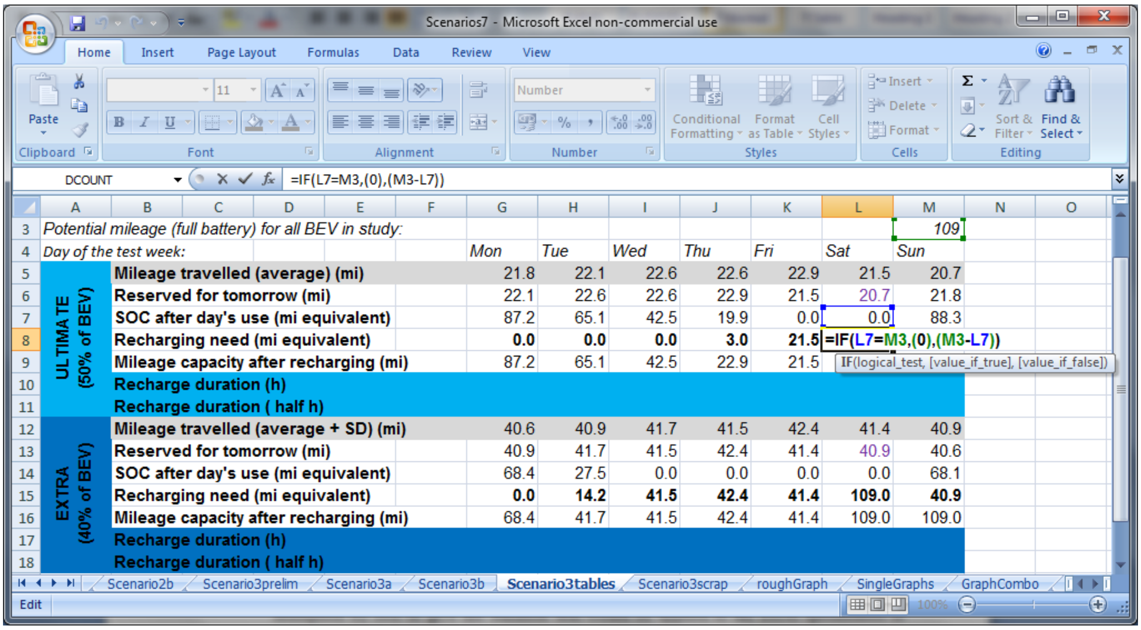
DCOUNT =G9-H5

	A	B	C	D	E	F	G	H	I	J	K	L	M
3	*Potential mileage (full battery) for all BEV in study:*												109
4	*Day of the test week:*						*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*	*Sun*
5	**ULTIMA TE (50% of BEV)**	**Mileage travelled (average) (mi)**					21.8	22.1	22.6	22.6	22.9	21.5	20.7
6		**Reserved for tomorrow (mi)**					22.1	22.6	22.6	22.9	21.5	20.7	21.8
7		**SOC after day's use (mi equivalent)**					87.2	=G9-H5					
8		**Recharging need (mi equivalent)**					**0.0**	**0.0**					
9		**Mileage capacity after recharging (mi)**					87.2	65.1					
10		**Recharge duration (h)**											
11		**Recharge duration (half h)**											
12	**EXTRA (40% of BEV)**	**Mileage travelled (average + SD) (mi)**					40.6	40.9	41.7	41.5	42.4	41.4	40.9
13		**Reserved for tomorrow (mi)**					40.9	41.7	41.5	42.4	41.4	40.9	40.6
14		**SOC after day's use (mi equivalent)**					68.4	27.5					
15		**Recharging need (mi equivalent)**					**0.0**	**14.2**					
16		**Mileage capacity after recharging (mi)**					68.4	41.7					
17		**Recharge duration (h)**											
18		**Recharge duration (half h)**											

A3.17. Building a table in Microsoft Excel 2007 to determine partial recharging patterns for BEV subgroups Ultimate and Extra. In this figure: applying formula to Tuesday using Monday as a template then altering "SOC after day's use (mi equivalent)" to incorporate the previous night's recovery of potential mileage to the battery by recharging.

Saturday's recharging need thus requires a calculation modification as follows. If it is true that the number of miles remaining in the battery after that day's use – cell L7 – is equal to the maximum potential mileage on a full battery – cell M3 – then the value returned is zero. In other words: there is no need for recharging.

If that statement is false, then the value that must be returned as the recharging need will be the maximum potential mileage on a full battery – cell M3 – minus the number of miles remaining in the battery after the day's use – cell L7. This is shown by A3.18. In order to be sure that vehicles start the week, as assumed, with a full battery, the same formula modifications must also be applied to Sunday's estimated recharging need.



=IF(L7=M3,(0),(M3-L7))

	A	B–F	G	H	I	J	K	L	M
3	*Potential mileage (full battery) for all BEV in study:*								*109*
4	*Day of the test week:*		*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*	*Sun*
5	**ULTIMA TE (50% of BEV)**	**Mileage travelled (average) (mi)**	21.8	22.1	22.6	22.6	22.9	21.5	20.7
6		**Reserved for tomorrow (mi)**	22.1	22.6	22.6	22.9	21.5	20.7	21.8
7		**SOC after day's use (mi equivalent)**	87.2	65.1	42.5	19.9	0.0	0.0	88.3
8		**Recharging need (mi equivalent)**	**0.0**	**0.0**	**0.0**	**3.0**	**21.5**	**=IF(L7=M3,(0),(M3-L7))**	
9		**Mileage capacity after recharging (mi)**	87.2	65.1	42.5	22.9	21.5	IF(logical_test, [value_if_true], [value_if_false])	
10		**Recharge duration (h)**							
11		**Recharge duration (half h)**							
12	**EXTRA (40% of BEV)**	**Mileage travelled (average + SD) (mi)**	40.6	40.9	41.7	41.5	42.4	41.4	40.9
13		**Reserved for tomorrow (mi)**	40.9	41.7	41.5	42.4	41.4	40.9	40.6
14		**SOC after day's use (mi equivalent)**	68.4	27.5	0.0	0.0	0.0	0.0	68.1
15		**Recharging need (mi equivalent)**	**0.0**	**14.2**	**41.5**	**42.4**	**41.4**	**109.0**	**40.9**
16		**Mileage capacity after recharging (mi)**	68.4	41.7	41.5	42.4	41.4	109.0	109.0
17		**Recharge duration (h)**							
18		**Recharge duration (half h)**							

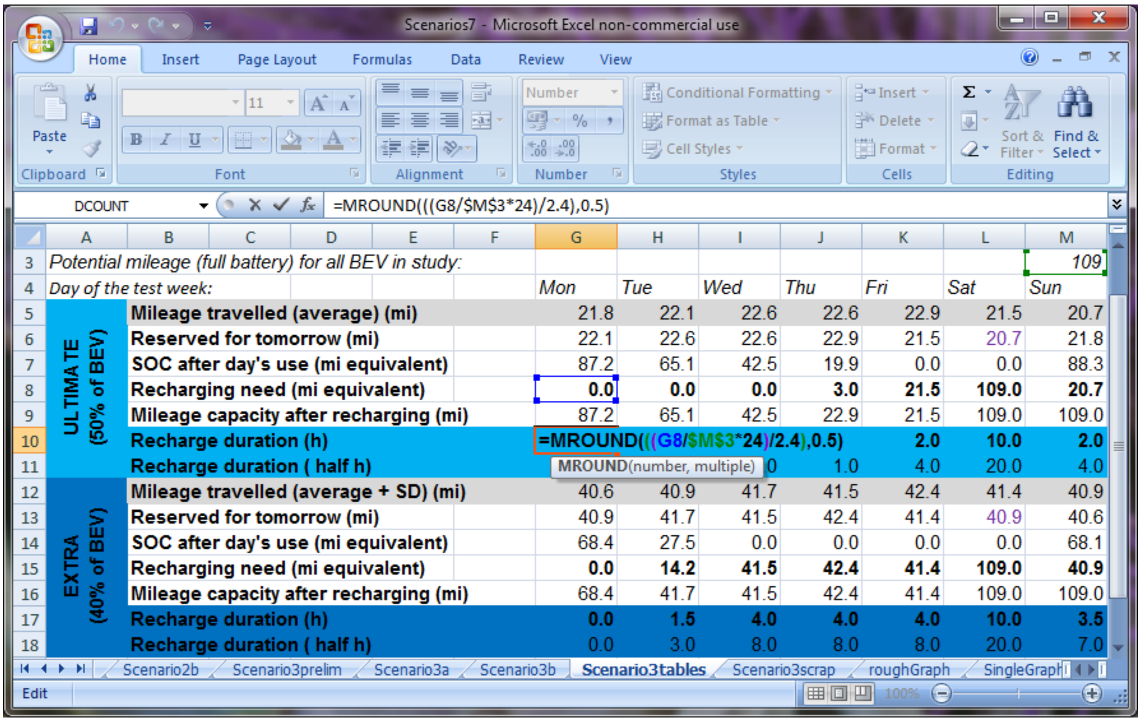
A3.18. Having used Tuesday as a template to copy formula to cells for all days, formulae for calculating recharging need for Saturday and Sunday night must be decoupled from next day's driving and instead return batteries to full SOC.

Step 6: Calculate recharge durations

Recharging durations for each day were calculated using the established recharging need – its equivalent in miles – divided by the maximum mileage potential on a full battery then multiplied by the battery's capacity (24 kWh) to give a proportion of battery usage, then divided by the vehicle's recharging rate (for a BEV: 2.4 kW/h).

Note, however, that the resolution of electricity demand data is half hourly. The figure therefore had to be rounded to the nearest half hour using the MROUND function in Excel, then, in the row below, multiplied by two to give the recharging duration. This recharging duration would be applied to the Excel spreadsheet to simulate recharging demands for the two subgroups *Ultimate* and *Extra*. The formula is explained in A3.19 for calculating Monday's recharge duration in hours.

This last stage successfully shifts load from workdays to weekends, or rather specifically to Friday night. This provides a proof of concept and the basis for the modified Recharging Regimes to be adopted in scenario 3. Note however that at this stage it is assumed to be acceptable that vehicles are reaching zero SOC on some days (an impractical assumption). In other words: what has been omitted so far from calculating recharging needs, is the necessity to ensure there is mileage left for emergencies.



DCOUNT

=MROUND(((G8/$M$3*24)/2.4),0.5)

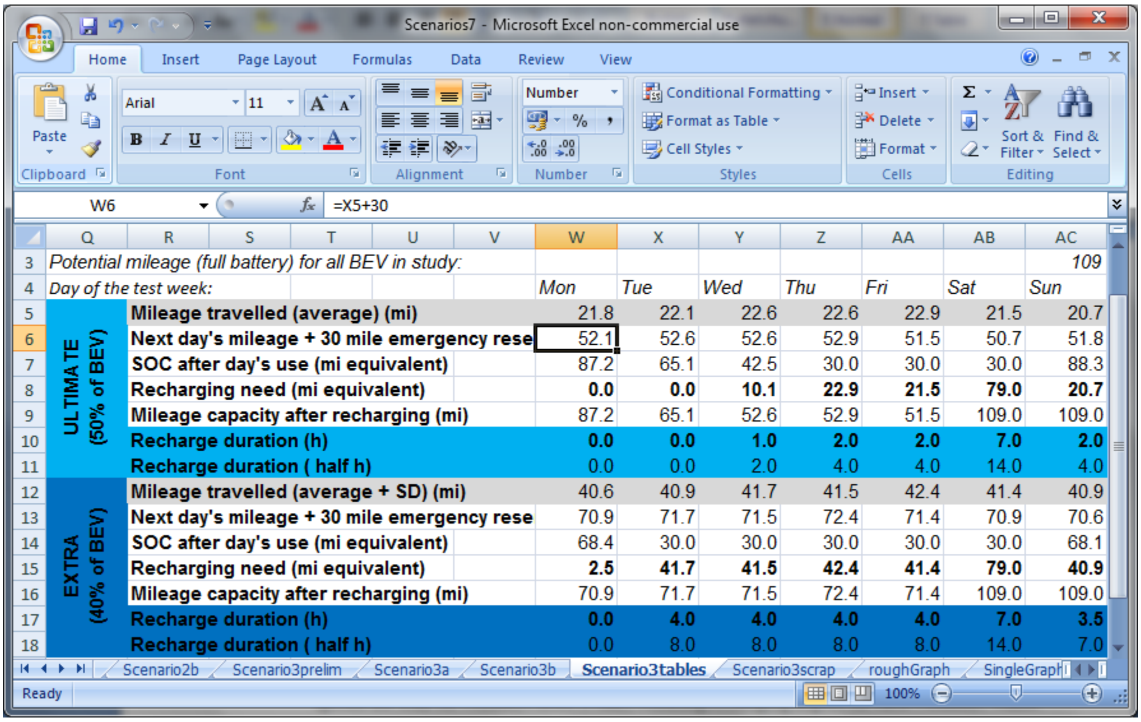
	A	B	G	H	I	J	K	L	M
3	*Potential mileage (full battery) for all BEV in study:*								*109*
4	*Day of the test week:*		*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*	*Sun*
5	**ULTIMA TE (50% of BEV)**	**Mileage travelled (average) (mi)**	21.8	22.1	22.6	22.6	22.9	21.5	20.7
6		**Reserved for tomorrow (mi)**	22.1	22.6	22.6	22.9	21.5	20.7	21.8
7		**SOC after day's use (mi equivalent)**	87.2	65.1	42.5	19.9	0.0	0.0	88.3
8		**Recharging need (mi equivalent)**	**0.0**	**0.0**	**0.0**	**3.0**	**21.5**	**109.0**	**20.7**
9		**Mileage capacity after recharging (mi)**	87.2	65.1	42.5	22.9	21.5	109.0	109.0
10		**Recharge duration (h)**	**=MROUND(((G8/$M$3*24)/2.4),0.5)**				**2.0**	**10.0**	**2.0**
11		**Recharge duration (half h)**	MROUND(number, multiple)		0	1.0	4.0	20.0	4.0
12	**EXTRA (40% of BEV)**	**Mileage travelled (average + SD) (mi)**	40.6	40.9	41.7	41.5	42.4	41.4	40.9
13		**Reserved for tomorrow (mi)**	40.9	41.7	41.5	42.4	41.4	40.9	40.6
14		**SOC after day's use (mi equivalent)**	68.4	27.5	0.0	0.0	0.0	0.0	68.1
15		**Recharging need (mi equivalent)**	**0.0**	**14.2**	**41.5**	**42.4**	**41.4**	**109.0**	**40.9**
16		**Mileage capacity after recharging (mi)**	68.4	41.7	41.5	42.4	41.4	109.0	109.0
17		**Recharge duration (h)**	**0.0**	**1.5**	**4.0**	**4.0**	**4.0**	**10.0**	**3.5**
18		**Recharge duration (half h)**	0.0	3.0	8.0	8.0	8.0	20.0	7.0

A3.19. Calculating recharge durations. For each day 'Recharging need (mi equivalent)' was divided by the maximum mileage potential when battery SOC is 100% then multiplied by the battery's capacity (24 kWh), then dividing that by the recharging rate for the vehicle (2.4 kW/h). Durations had to be rounded to the nearest half hour to match half-hourly national electricity demand data using the formula function 'MROUND'.

Step 5: Making allowance for an emergency mileage reserve

The Recharging Regimes for scenario 3A require one more additional modification before they can be applied: allowance must be made for emergency and unplanned travel. As noted in Chapter 8, emergencies happen and any unplanned events affect a person's travel needs. Consultation of literature in Chapter 8 suggested that an emergency mileage reserve of between 20 and 30 miles should suffice and in day-to-day life the allowance would act as a buffer for unplanned trips.

In the Excel spreadsheet the cells in the rows that returned values for the reserve mileage required for next day's driving, were edited to include the addition of 30 miles. Fig. A3.20 shows the new table of information following this edit, with the formula for the first cell of the row for *Ultimate* subgroups visible in the formula bar as "X5+30" as a given example. Final modifications for recharging duration for the *Ultimate* subgroups are given in Table A3-12 and for the *Extra* subgroups in Table A3-13.



W6 =X5+30

	Q–V		W	X	Y	Z	AA	AB	AC
3	*Potential mileage (full battery) for all BEV in study:*								*109*
4	*Day of the test week:*		*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*	*Sun*
5	**ULTIMA TE (50% of BEV)**	**Mileage travelled (average) (mi)**	21.8	22.1	22.6	22.6	22.9	21.5	20.7
6		**Next day's mileage + 30 mile emergency rese**	52.1	52.6	52.6	52.9	51.5	50.7	51.8
7		**SOC after day's use (mi equivalent)**	87.2	65.1	42.5	30.0	30.0	30.0	88.3
8		**Recharging need (mi equivalent)**	**0.0**	**0.0**	**10.1**	**22.9**	**21.5**	**79.0**	**20.7**
9		**Mileage capacity after recharging (mi)**	87.2	65.1	52.6	52.9	51.5	109.0	109.0
10		**Recharge duration (h)**	**0.0**	**0.0**	**1.0**	**2.0**	**2.0**	**7.0**	**2.0**
11		**Recharge duration (half h)**	0.0	0.0	2.0	4.0	4.0	14.0	4.0
12	**EXTRA (40% of BEV)**	**Mileage travelled (average + SD) (mi)**	40.6	40.9	41.7	41.5	42.4	41.4	40.9
13		**Next day's mileage + 30 mile emergency rese**	70.9	71.7	71.5	72.4	71.4	70.9	70.6
14		**SOC after day's use (mi equivalent)**	68.4	30.0	30.0	30.0	30.0	30.0	68.1
15		**Recharging need (mi equivalent)**	**2.5**	**41.7**	**41.5**	**42.4**	**41.4**	**79.0**	**40.9**
16		**Mileage capacity after recharging (mi)**	70.9	71.7	71.5	72.4	71.4	109.0	109.0
17		**Recharge duration (h)**	**0.0**	**4.0**	**4.0**	**4.0**	**4.0**	**7.0**	**3.5**
18		**Recharge duration (half h)**	0.0	8.0	8.0	8.0	8.0	14.0	7.0

Fig. A3.20. Vehicles from both *Ultimate* and *Extra* subgroups are allocated a 30 miles emergency reserve. The scheduled recharging must now ensure sufficient SOC remains to match the next day's expected mileage plus the emergency reserve.

Table A3-12: Load duration modifications made and load shifted per vehicle in kWh per day of the week for BEV in *Ultimate* subgroups.

Day of week	Previous duration (h)	Modified duration (h)	Previous energy consumption (kWh)	New energy consumption (kWh)	Load shift (difference in kWh)
Monday	2.0	0.0	4.8	0.0	-4.8
Tuesday	2.0	0.0	4.8	0.0	-4.8
Wednesday	2.0	1.0	4.8	2.4	-2.4
Thursday	2.0	2.0	4.8	4.8	0.0
Friday	2.0	2.0	4.8	4.8	0.0
Saturday	2.0	7.0	4.8	16.8	+12
Sunday	2.0	2.0	4.8	4.8	0.0
Weekly total	**14.0**	**14.0**	**33.6**	**33.6**	**0.0**

Table A3-13: Load duration modifications made and load shifted per vehicle in kWh per day of the week for BEV in *Extra* subgroups.

Day of week	Previous duration (h)	Modified duration (h)	Previous energy consumption (kWh)	New energy consumption (kWh)	Load shift (difference in kWh)
Monday	3.5	0.0	8.4	0.0	-8.4
Tuesday	4.0	4.0	9.6	9.6	0.0
Wednesday	4.0	4.0	9.6	9.6	0.0
Thursday	4.0	4.0	9.6	9.6	0.0
Friday	4.0	4.0	9.6	9.6	0.0
Saturday	4.0	7.0	9.6	16.8	+7.2
Sunday	3.5	3.5	8.4	8.4	0.0
Weekly total	**27.0**	**26.5**	**64.8**	**63.6**	**-1.2**

Please note that a discrepancy has been introduced: it appears in Table A3-13 that vehicles in Extra subgroups are recharging for half an hour less over the week following modification compared to previous durations in 1B and 2B for vehicles travelling the same daily mileages. This is due to rounding recharging need to the nearest half hour based on daily mileages, not the weekly total required then being distributed over the days of the week in 1B, 2B, 3A and 3B. Vehicles travelling the average plus the SD mileage on each day travel a total of 289.4 miles, requiring a total of just over 13 h to recover SOC to full over the whole week.

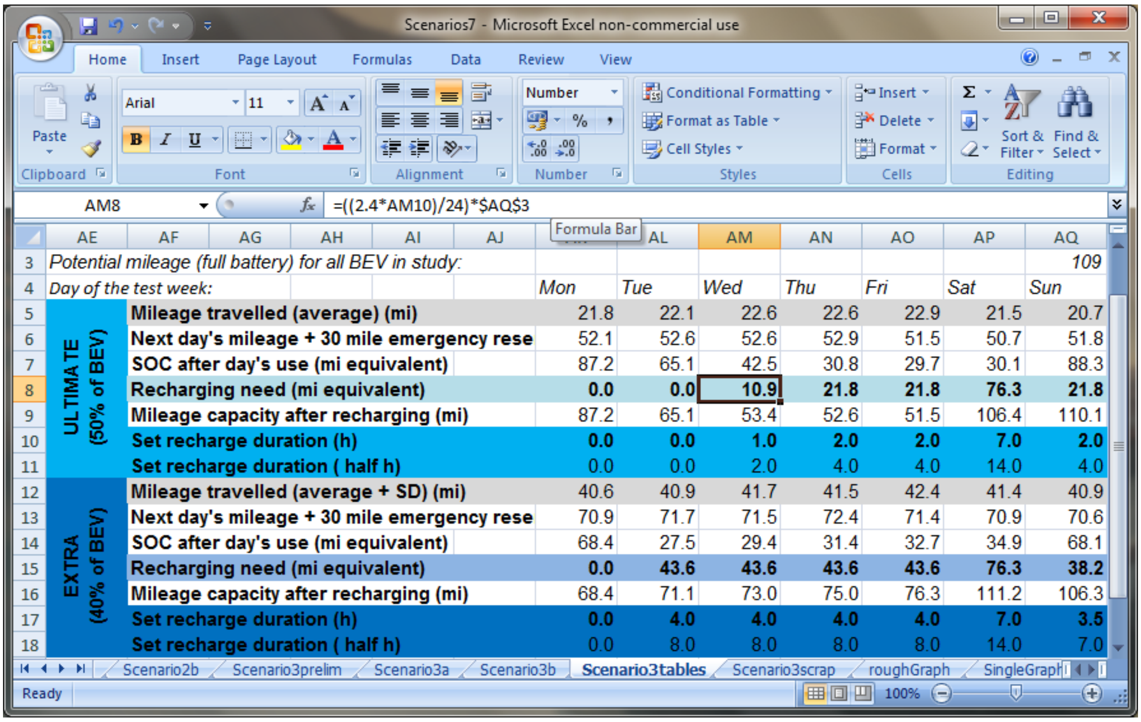
ADVANCED LOAD-SHIFTING: LOAD LEVELLING (3B)

In 3B, the modified Recharging Regimes from 3A, including the allowance for emergency mileage reserve, are further modified to level loads on workdays over all workdays and to level loads on weekend days over the weekend period. 3B is identical to 3A in every way but one: slight modifications have been made to the recharging durations of BEV in the subgroups used for load-shifting (*Ultimate* and *Extra*).

In Excel a copy of the table constructed for basic load-shifting in Fig. A3.20 was edited to switch the direction of calculations relating to recharging need and recharging duration. In Fig. A3.20 (used as is for scenario 3A) recharging need was used to calculate recharging duration for each day of the week. In 3B however the table works the other way around so that recharging need is determined by recharging duration, which was then manually altered to give a more even spread of loads between Monday and Thursday and between Friday and Sunday.

Initially the cells for recharging duration were copied and then pasted using the ‘Paste special’ option as ‘values’ to replace the cells that were being copied. Having done this, the cells for calculating recharging need could be edited to relate to recharging duration, the cells for which would no longer change when any other value in the table changed.

The equation for calculating recharging need is given in the formula bar in Fig. A3.21 for Wednesday’s recharging need, which equals: the hourly recharging rate (2.4 kW/h) of the BEV multiplied by the newly set recharge duration (given in h in cell AM10), divided by the BEV battery capacity (24 kWh), then multiplied by the potential mileage range of the BEV when it has a full battery (given in cell AQ3).



AM8 =((2.4*AM10)/24)*$AQ$3

3	*Potential mileage (full battery) for all BEV in study:*								*109*
4	*Day of the test week:*		*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*	*Sun*
5	**ULTIMATE (50% of BEV)**	**Mileage travelled (average) (mi)**	21.8	22.1	22.6	22.6	22.9	21.5	20.7
6		**Next day's mileage + 30 mile emergency rese**	52.1	52.6	52.6	52.9	51.5	50.7	51.8
7		**SOC after day's use (mi equivalent)**	87.2	65.1	42.5	30.8	29.7	30.1	88.3
8		**Recharging need (mi equivalent)**	**0.0**	**0.0**	**10.9**	**21.8**	**21.8**	**76.3**	**21.8**
9		**Mileage capacity after recharging (mi)**	87.2	65.1	53.4	52.6	51.5	106.4	110.1
10		**Set recharge duration (h)**	**0.0**	**0.0**	**1.0**	**2.0**	**2.0**	**7.0**	**2.0**
11		**Set recharge duration (half h)**	0.0	0.0	2.0	4.0	4.0	14.0	4.0
12	**EXTRA (40% of BEV)**	**Mileage travelled (average + SD) (mi)**	40.6	40.9	41.7	41.5	42.4	41.4	40.9
13		**Next day's mileage + 30 mile emergency rese**	70.9	71.7	71.5	72.4	71.4	70.9	70.6
14		**SOC after day's use (mi equivalent)**	68.4	27.5	29.4	31.4	32.7	34.9	68.1
15		**Recharging need (mi equivalent)**	**0.0**	**43.6**	**43.6**	**43.6**	**43.6**	**76.3**	**38.2**
16		**Mileage capacity after recharging (mi)**	68.4	71.1	73.0	75.0	76.3	111.2	106.3
17		**Set recharge duration (h)**	**0.0**	**4.0**	**4.0**	**4.0**	**4.0**	**7.0**	**3.5**
18		**Set recharge duration (half h)**	0.0	8.0	8.0	8.0	8.0	14.0	7.0

Fig. A3.21. Introducing partial recharging: recharging need must be switched from being calculated from next day’s mileage to instead reflect the duration of recharging that has been set for vehicles on each day.

Note that in the Fig. A3.21 the last cell mentioned is actually written ‘$AQ$3’. Inserting a ‘$’ before the letter identification for a cell ensures the formula in the destination cell will refer to a cell in the same column as referred to by the formula in the copied cell. Inserting a ‘$’ before the number identification for a cell ensures the formula in the destination cell will refer to a cell in the same row as referred to by the formula in the copied cell.

Excel will otherwise automatically select a cell for the formula that is in identical proximity to the destination cell as the cell in the original formula was to the cell from which the formula was first copied. So, inserting a ‘$’ before both the letter and the number of a cell’s identification in a formula will ensure that the very same cell will be referred to by the formula, regardless of to where on the spreadsheet the formula is copied.

As can be noted by comparing the resulting value for cell AM8 between Fig. A3.21 and previous Fig. A3.20, there are also consequences for working backwards from recharge duration to determine the number of miles returned to batteries after recharging each night. This is because recharging durations can only be set to an accuracy of half an hour in order to match the half hourly electricity demand data used, which in this study is assumed equivalent to 5.5 miles worth of SOC recovery to BEV batteries. This has had two consequences:

- the assumed emergency reserved mileage had to be assumed to range between two values and
- the estimated mileage capacity of the battery had to be assumed not to exceed the maximum potential mileage range of the vehicle, but to equal it in instances where calculations led to figures that suggested the battery was holding more charge than possible i.e. greater than SOC = 100%.

The first consequence meant that for this variation, the allowance for emergencies is had to be permitted to vary, so long as it does not fall below the minimum of 20 miles. The addition or subtraction of a half hour's recharging could not be used to ensure that exactly the right amount of next day's mileage, plus the 30 mile maximum emergency reserve mileage, would be present in the battery post recharging. Figures had to be adjusted to be close to the ideal, give or take 5.5 miles.

Conditional formatting was used to highlight cells when alterations to recharging durations on any day lead to a mileage after recharging that was less than the number of miles required for driving tomorrow plus the minimum 20 miles emergency and unplanned travel reserve. This was achieved by selecting Conditional Formatting from the 'Home' ribbon on the Excel spreadsheet. Then selecting 'Highlight Cells Rules' from the drop down menu, select next 'Less Than...' to bring up a window for defining the criteria for formatting and the type of formatting to be used if the criteria are fulfilled.

Fig. A3.22 shows for cell AK9 the conditional formatting that was thus applied ("Light Red Fill with Dark Red Text") to "Format cells that are LESS THAN" the next day's mileage plus the 30 mile emergency and unplanned travel reserve[24] (cell AK6) minus 10. Multiple rules can be applied to a cell, so additional rules can be added that highlight cells when the number of battery miles after recharging is greater than tomorrow's mileage plus 30 miles, or for example exceeds the maximum potential mileage range for a BEV with a full battery. This adapts the

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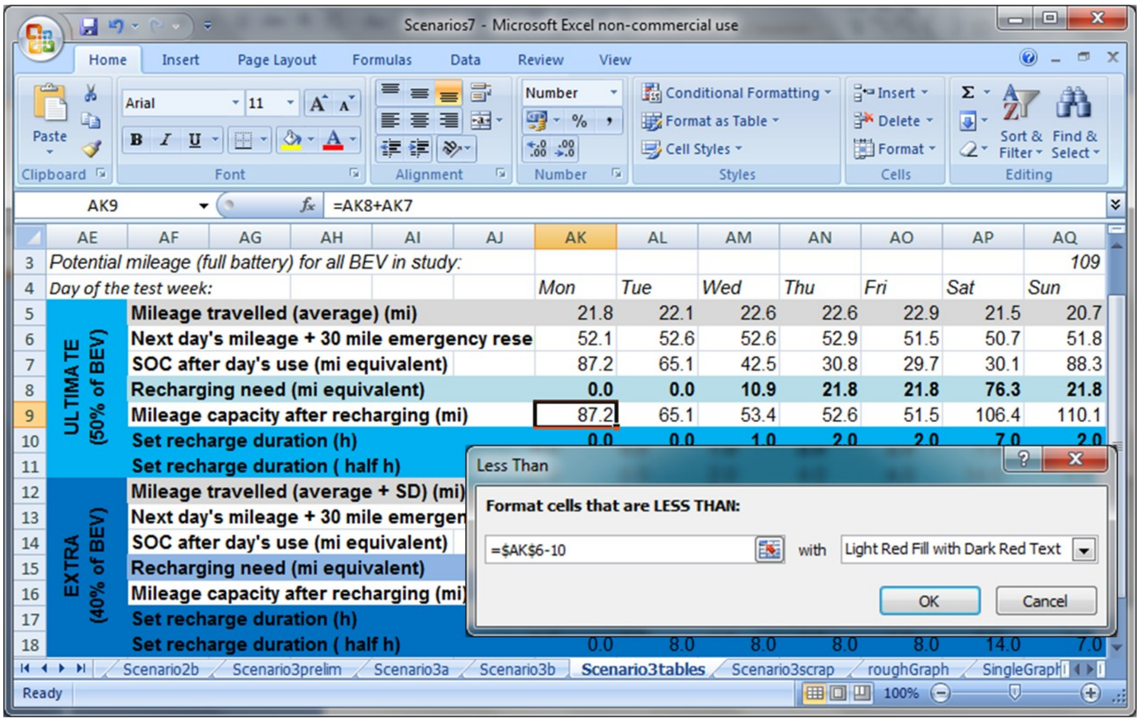
[24] 20 miles is deemed the minimum permissible emergency mileage allowance, 30 miles is deemed to be the maximum. In the basic load-shifting technique (scenario 3A) that allowance was set to 30 miles. Here (scenario 3B), however, conditional formatting is being used to indicate when SOC falls below the minimum allowance 20 miles.

basic load levelling technique adopted in 3A which assumed a 30 mile emergency and unplanned travel allowance to one that assumes emergency and unplanned travel allowance is permissible so long as it falls within a range of between 20 and 30 miles, as was originally specified.

The latter conditional formatting was used to identify instances of the second consequence where the addition or subtraction of half an hour's recharging over the course of the weekend could not exactly return the battery's mileage equivalent SOC to full (i.e. 109 miles) and instead went over it. In reality there are mechanisms involved in recharging batteries that protect them from over-charging. So although the figures imply more than 109 miles are available for use from the vehicle at the end of Sunday's recharging, it was assumed these were simply recharged to 100% SOC.



AK9 =AK8+AK7

	AE	AF	AK	AL	AM	AN	AO	AP	AQ
3	*Potential mileage (full battery) for all BEV in study:*								*109*
4	*Day of the test week:*		*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*	*Sun*
5	**ULTIMA TE (50% of BEV)**	**Mileage travelled (average) (mi)**	21.8	22.1	22.6	22.6	22.9	21.5	20.7
6		**Next day's mileage + 30 mile emergency rese**	52.1	52.6	52.6	52.9	51.5	50.7	51.8
7		**SOC after day's use (mi equivalent)**	87.2	65.1	42.5	30.8	29.7	30.1	88.3
8		**Recharging need (mi equivalent)**	**0.0**	**0.0**	**10.9**	**21.8**	**21.8**	**76.3**	**21.8**
9		**Mileage capacity after recharging (mi)**	87.2	65.1	53.4	52.6	51.5	106.4	110.1
10		**Set recharge duration (h)**	0.0	0.0	1.0	2.0	2.0	7.0	2.0
11		**Set recharge duration (half h)**							
12	**EXTRA (40% of BEV)**	**Mileage travelled (average + SD) (mi)**							
13		**Next day's mileage + 30 mile emergen**							
14		**SOC after day's use (mi equivalent)**							
15		**Recharging need (mi equivalent)**							
16		**Mileage capacity after recharging (mi)**							
17		**Set recharge duration (h)**							
18		**Set recharge duration (half h)**	0.0	8.0	8.0	8.0	8.0	14.0	7.0

Less Than

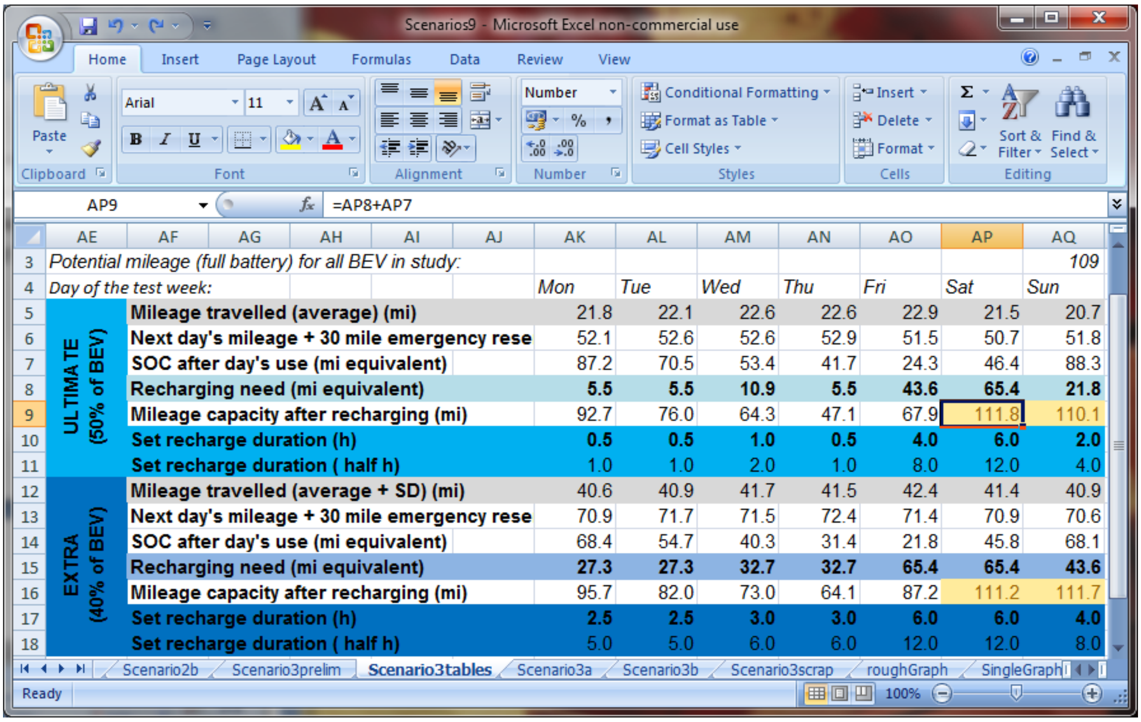
Format cells that are LESS THAN:

=$AK$6-10 with Light Red Fill with Dark Red Text

OK Cancel

Fig. A3.22. Conditional formatting applied to cell AK9. The cell font will change to dark red and the cell will be highlighted with light red if the value in the cell equals: the next day's required mileage plus 30 mile emergency reserve, minus 10. In other words, the "Next day's mileage" caps the required miles for tomorrow at the upper limit of the emergency reserve, whilst the conditional formatting will highlight the cell if the value falls below the minimum that must be reserved: the next day's mileage plus 20 miles emergency reserve.

So, durations were first set to give the most even spread over workdays for recharging that occurred on workdays, over weekend days for recharging that occurred over weekend days. The conditional formatting was used to help ensure that when batteries were numerically over-recharged this was by the smallest amount, adjusting durations to suit. Conditional formatting was also used to ensure that on no day was the recharging duration insufficient to provide at least 20-30 miles of emergency reserve on top of that expected to be required for next day's mileage. The results can be seen in Fig. A3.23, which also highlights instances where vehicle batteries would be theoretically overcharged based on the recharging duration set.

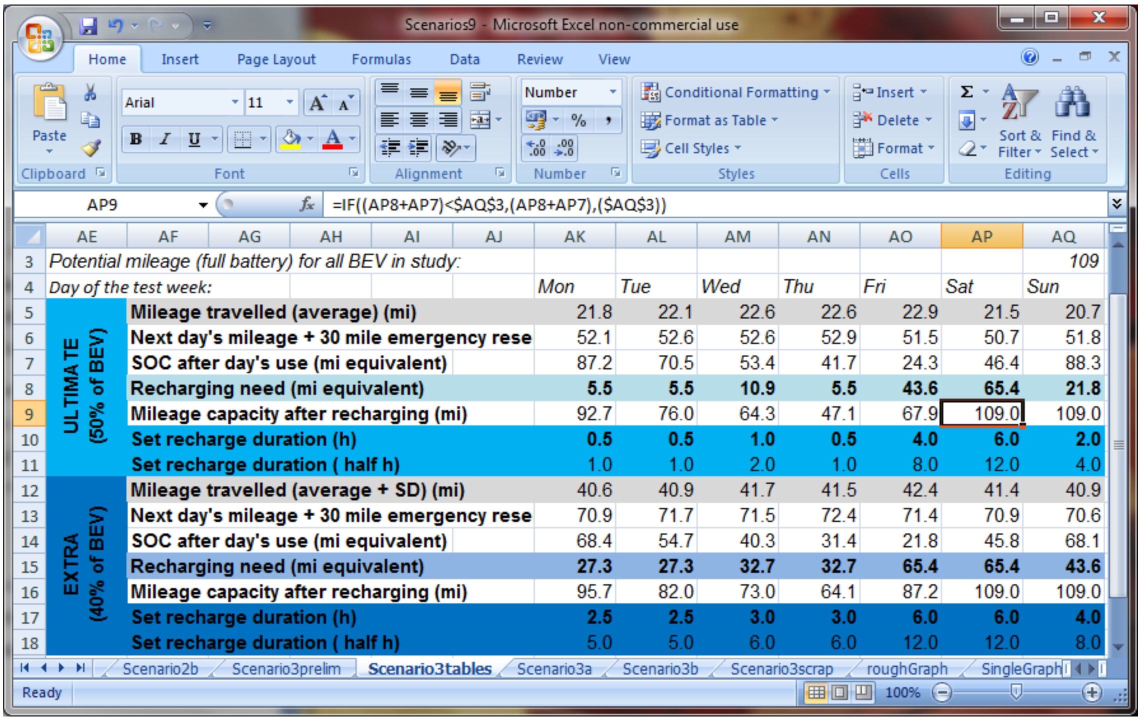


AP9 =AP8+AP7

	AE	AF	AK	AL	AM	AN	AO	AP	AQ
3	*Potential mileage (full battery) for all BEV in study:*								*109*
4	*Day of the test week:*		*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*	*Sun*
5	**ULTIMATE (50% of BEV)**	**Mileage travelled (average) (mi)**	21.8	22.1	22.6	22.6	22.9	21.5	20.7
6		**Next day's mileage + 30 mile emergency rese**	52.1	52.6	52.6	52.9	51.5	50.7	51.8
7		**SOC after day's use (mi equivalent)**	87.2	70.5	53.4	41.7	24.3	46.4	88.3
8		**Recharging need (mi equivalent)**	**5.5**	**5.5**	**10.9**	**5.5**	**43.6**	**65.4**	**21.8**
9		**Mileage capacity after recharging (mi)**	92.7	76.0	64.3	47.1	67.9	111.8	110.1
10		**Set recharge duration (h)**	**0.5**	**0.5**	**1.0**	**0.5**	**4.0**	**6.0**	**2.0**
11		**Set recharge duration (half h)**	1.0	1.0	2.0	1.0	8.0	12.0	4.0
12	**EXTRA (40% of BEV)**	**Mileage travelled (average + SD) (mi)**	40.6	40.9	41.7	41.5	42.4	41.4	40.9
13		**Next day's mileage + 30 mile emergency rese**	70.9	71.7	71.5	72.4	71.4	70.9	70.6
14		**SOC after day's use (mi equivalent)**	68.4	54.7	40.3	31.4	21.8	45.8	68.1
15		**Recharging need (mi equivalent)**	**27.3**	**27.3**	**32.7**	**32.7**	**65.4**	**65.4**	**43.6**
16		**Mileage capacity after recharging (mi)**	95.7	82.0	73.0	64.1	87.2	111.2	111.7
17		**Set recharge duration (h)**	**2.5**	**2.5**	**3.0**	**3.0**	**6.0**	**6.0**	**4.0**
18		**Set recharge duration (half h)**	5.0	5.0	6.0	6.0	12.0	12.0	8.0

Fig. A3.23. Conditional formatting rules applied to row 9 highlight when the mileage after recharging is above the maximum possible for the vehicle battery.

Now there is a requirement to modify the formula in the rows for mileage capacity after recharging so that if the SOC after day's use plus the number of miles estimated as the recharging need equals a number higher than the maximum potential mileage of the BEV, the value returned will be the maximum potential mileage of the BEV. See Fig. A3.24 for a display of the modified formula in the formula as exampled by cell AP9 and results of the change.



AP9 =IF((AP8+AP7)<$AQ$3,(AP8+AP7),($AQ$3))

	AE–AJ		AK	AL	AM	AN	AO	AP	AQ
3	Potential mileage (full battery) for all BEV in study:								109
4	Day of the test week:		Mon	Tue	Wed	Thu	Fri	Sat	Sun
5	ULTIMA TE (50% of BEV)	Mileage travelled (average) (mi)	21.8	22.1	22.6	22.6	22.9	21.5	20.7
6		Next day's mileage + 30 mile emergency rese	52.1	52.6	52.6	52.9	51.5	50.7	51.8
7		SOC after day's use (mi equivalent)	87.2	70.5	53.4	41.7	24.3	46.4	88.3
8		Recharging need (mi equivalent)	5.5	5.5	10.9	5.5	43.6	65.4	21.8
9		Mileage capacity after recharging (mi)	92.7	76.0	64.3	47.1	67.9	109.0	109.0
10		Set recharge duration (h)	0.5	0.5	1.0	0.5	4.0	6.0	2.0
11		Set recharge duration (half h)	1.0	1.0	2.0	1.0	8.0	12.0	4.0
12	EXTRA (40% of BEV)	Mileage travelled (average + SD) (mi)	40.6	40.9	41.7	41.5	42.4	41.4	40.9
13		Next day's mileage + 30 mile emergency rese	70.9	71.7	71.5	72.4	71.4	70.9	70.6
14		SOC after day's use (mi equivalent)	68.4	54.7	40.3	31.4	21.8	45.8	68.1
15		Recharging need (mi equivalent)	27.3	27.3	32.7	32.7	65.4	65.4	43.6
16		Mileage capacity after recharging (mi)	95.7	82.0	73.0	64.1	87.2	109.0	109.0
17		Set recharge duration (h)	2.5	2.5	3.0	3.0	6.0	6.0	4.0
18		Set recharge duration (half h)	5.0	5.0	6.0	6.0	12.0	12.0	8.0

Fig. A3.24. In the formula bar the modified formula for cell AP9 is shown. If the recharging need for Sunday plus the SOC remaining after Saturday's use is smaller than the maximum mileage potential of the BEV when it has a full battery, then the cell value returned will be exactly that. If the cell value is however greater than that calculation, the value returned is the maximum mileage potential of the vehicle when it has a full battery – in other words the battery is simply assumed to be 'recharged to full'.

Please note that a discrepancy has been introduced: it appears in Fig. A3.24 that vehicles in *Ultimate* subgroups are recharging for half an hour more over the week following modification compared to previous durations in 1B and 2B for vehicles travelling the same daily mileages. This is due to rounding recharging need to the nearest half hour based on daily mileages, not the weekly total required then being distributed over the days of the week in 1B, 2B, 3A and 3B. Vehicles travelling the average mileage on each day travel a total of 154.1 miles, requiring a total of just over 7 h to recover SOC to full over the whole week.

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