

Analysis of the Distribution of Financial Benefits of BEV Integrated Residential Energy Systems: Integration Including Optimal Charging Scheduling and Energy Management of BEV and Residential Energy Demands

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Acknowledgement

Dear mum and dad.

Thank you. For everything. Always.

끊임 없는 사랑과 이해를 진심으로 감사드립니다.

To my father who supported us to help me get to where I am.

To my mother who raised me on her own whilst doing her own PhD. Neither of them easy tasks individually; much harder simultaneously.

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- 2012-2022 -

Carpe diem. C'est la vie. Je ne regrette rien. Tempus fugit velut umbra.

Thank you.

행운을 빕니다.

Declaration

The research that is presented in this thesis is my own, except where the work of others is reference.

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Abstract

Charging scheduling of Battery Electric Vehicles (BEV) poses challenges to individual users due to the large amount of information to be considered. BEV users could benefit financially by optimizing their charging scheduling. They could also benefit by integrating their BEV with their wider residential energy system. This integration can involve H2V, V2H, H2G, real-time electricity tariffs, residential BESS and PV. BEV users could also provide benefits for the wider energy system, such as through grid load balancing.

In this thesis, the extent of financial benefits for users of optimized BEV charging and distribution of the benefits across society are analysed. Assessing this distribution is important to ensure equitable BEV, BESS and PV adoption and usage, as different segments of society could benefit differentially. Previous studies have presented optimizing charging scheduling, however, few studies quantitatively assessed the distribution and extent of the benefits across demographics and socio-economic factors. This thesis addresses that gap.

London was used as the case study. How the benefits are distributed across demographic characteristics of household income, ethnicity, and employment status, and correlated with welfare indicators are addressed. The effects of the different components of integration on extent of the benefits are analysed. The findings show that there is differential distribution of the benefits across demographic characteristics of income, ethnicity, and employment status. The benefits can be as much as £0.2855 higher per day (£104 per year). Technologies that enable integration between the BEV, home, and the grid (V2H, H2V, H2G, TOU), and access to BESS and PV were found to have positive benefits. These findings imply that policies are required if equitable distribution of benefits of optimized BEV adoption and charging is desired.

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<i>Abbreviations</i>			
	Battery energy storage		
BESS	system	LTDS	London Travel Data Survey
BEV	Battery electric vehicle	MES	Mobile energy storage
	Climate monitoring satellite		
CMSAF	application facility	MIH	Middle-income households
CSP	Charging service provider	MILP	Mixed integer linear programming
			National energy efficiency data-
DER	Distributed energy resources	NEED	framework
DSR	Demand side response	NHTS	National household travel survey
DST	Decision support tool	PEV	Plug-in electric vehicles
	Electric vehicle Supply		
EVSE	Equipment	PHEV	Plug-in hybrid electric vehicles
FB	Financial benefit	PV	Photovoltaic
			Photovoltaic geographical
FIT	Feed-in-Tariff	PVGIS	information system
GHG	Greenhouse gas	RES	renewable energy sources
	Generalized variance inflation		
GVIF	factor	SBO	Smart building operator
H2G	Home-to-grid	SEG	Small export guarantee
H2V	Home-to-vehicle	TOU	Time-of-use
	Home energy management		
HEMS	system	ULEV	Ultra-low emission vehicles
HIH	High-income households	V2G	Vehicle-to-grid
	Internal combustion engine		
ICEV	vehicles	V2H	Vehicle-to-home
IMD	Index of multiple deprivation	V2B	Vehicle-to-building
LIH	Low-income households	V2H2G	Vehicle-to-home-to-grid
LP	Linear programming	VIF	Variance inflation factor
<i>Symbols</i>			
Subscript t	Set of time indices		
Subscript i	Set of stays in the trip	dt	Time resolution segment
	itinerary		
A_t	Arrival time: the set of times at which EV arrives at time t, or stay i	soe_t^{EVA}	State of Energy of EV (kWh) at arrival at time t or stay i

D_t	Departure time: the set of times at which EV departs from stay i	soe_t^{EVD}	State of Energy of EV (kWh) at departure from time t
Q_t	Energy charged by EV at t [kWh]	soe_{cap}^{EV}	Capacity of EV battery (kWh)
G_t	V2G at t [kWh]	P_t^{EV}	Electricity transfer rate (kW) of EV at t
C_t	Cost to charge EV at time t [£/kWh]	p^{EVmax}	Maximum power with which EV can be charged
R_t	Revenue from V2G at t [£/kWh]	soe_t^{ESSA}	State of Energy of BESS (kWh) at arrival at time t
SH_t	Energy from BESS to home at t [kWh]	soe_t^{ESSD}	State of Energy of BESS (kWh) at departure from time t
HS_t	Energy from home to BESS at t [kWh]	soe_{cap}^{ESS}	Capacity of BESS battery (kWh)
VH_t	Energy from EV to home at t [kWh]	P_t^{ESS}	Electricity transfer rate of BESS (kW) at t
HV_t	Energy from home to EV at t [kWh]	p^{ESSmax}	Maximum power with which BESS can be charged (kW)
H_t	Residential energy demand at t [kWh]	dos_i	Duration of Stay at stay i
I_t	Income from V2H [£/kWh]	doc_i	Duration of Charge at location i
B_t	Cost of residential energy bill [£/kWh]	d_i	Distance to travel (km) from stay i to stay i+1
PV_t	PV generation at time t [kW]	f	Fuel economy of EV (kWh/km)

Chapter 1

Introduction

There are global efforts to electrify road transport through the uptake of electric vehicles (EVs) to replace internal combustion engine vehicles (ICEV). By 2030, 7% or 12% of the of road vehicles could be electric depending on the scenario (IEA, 2021). 33% of the global vehicle fleet is predicted to be electric by 2040 (Bloomberg, 2018). The trend of EV adoption is increasing. There were 10 million EVs globally by the end of 2020. 3 million EVs were sold globally in 2020. EVs are gaining a large share of the vehicle fleet, as there was a 41% increase in EV registration, even though global car sales (including non EVs) dropped by 6% (IEA, 2021). This study will focus on battery EVs (BEV) specifically (EVs that solely use electricity as a source of energy), noting that the operating and charging consideration of a BEVs and plug-in hybrid EVs (PHEV) differ (further discussed in Subsection 1.1.1).

There are many benefits of electrification of transport discussed in the literature. The analysis of benefits to users, the implications of the distribution of the benefits across society, and the implications to organizations and businesses are of concern and importance. The benefits for society include direct benefits, such as reducing road transport related urban air pollution and greenhouse gas (GHG) emissions, and indirect benefits such as the usage of renewable energy sources (RES) as the source of energy for road transportation. Furthermore, there can be benefits from synergies and interactions between EVs and the energy system through electricity transfers (vehicle-to-home-to-grid (V2H2G)). These interactions and synergies are enabled by EVs' ability to store electrical energy, and act as mobile energy storage (MES).

Analysis of the potential benefits from analysing the integration of BEV charging demands and scheduling based on the travel itinerary of the BEV user, with potential for V2H2G, and RES utilization would be an important novel, interesting and impactful extension to the field. This would aid in better understanding where and when the BEVs can interact with Electric Vehicle Supply Equipment (EVSE) for the benefit of the user and system through optimizing charging scheduling, as well as participating in V2H2G, and increasing utilisation of renewable energy sources (RES). As such, a quantitative analysis of the benefits of optimizing the scheduling of charging of BEVs for individuals based on their travel patterns, with the BEVs integrating with the different components of the system (V2H2G and RES) is proposed. The analysis of the distribution of these benefits across society is an important contribution

to the field to assess the equity of adoption of these technologies. The terms mentioned above are further discussed and described in Section 1.1.

This chapter outlines the context of the research. Section 1.1 details the changes in society which set the context and need for the research. The changes include electrification of vehicles and changes in the energy system. The different changes will be defined and described within this Subsection. Section 1.2 outlines the aims and objectives of the research. Section 1.3 outlines the contributions of the research. Section 1.4 outlines the structure of the rest of the thesis.

1.1 Background and context for integrating the energy system environment of an individual EV user

An EV user could have access to several energy technologies, which can form their energy system environment. This system could be integrated to allow the different technologies to work together, with bi-directional electricity flows between them. Three key elements that allow the system to integrate are:

- The electrification of the transportation sector through adoption of EVs.
- The changes in the energy system such as increasing RES, distributed energy resources (DER) and smart meters. DER and smart meters are further discussed in Subsections 1.1.2 and 1.1.3.
- The ability of EVs to interact bidirectionally with the energy system.

1.1.1 Electrification of vehicles

For clarity, there are several types of EVs, split broadly into two categories: Hybrid Electric Vehicles (HEVs) and Plug-in electric vehicles (PEVs). HEVs use both a battery and ICE, but predominantly run on the ICE and cannot be plugged in to charge the battery. PEVs plug in to charge the battery. Within PEVs there are Plug-in hybrid electric vehicles (PHEVs), and Battery Electric Vehicles (BEVs). The former can run on both electricity and traditional fuel and can be plugged in to charge. The latter only has a battery and relies solely on electricity as fuel. This research will concentrate on BEVs. The research will refer to EVs more generally when referring to previous studies which are based on different types of EVs. Some of the concepts within this research will apply to some extent to other types of EVs beyond BEVs, but the main crux of the research will be based on the operations of BEVs specifically. The analysis in this thesis will focus on privately owned vehicles. The importance of fleets in urban areas

is recognised, as taxis, ride hailing companies, for example, can make up a large number of vehicles on the roads, and can have very different charging needs. However, the scope is limited to privately owned vehicles as the main aim of the research is on analysing the equity of distribution of financial benefits, and thus, focusing on privately owned vehicles is appropriate.

In line with the drive to increase EV adoption, many cities and countries have plans to ban ICEVs, or the sale of ICEVs, from early 2020s to 2040. Paris, Madrid, Athens and Mexico City (The Guardian, 2016), amongst other cities, aim to end the use of all diesel vehicles by 2025. United States (Forbes, 2020), Germany (Climate Action, 2016), UK (GOV.UK, 2020), and India (Washington Post, 2020), amongst other countries, aim to ban gasoline and diesel vehicles by 2030. The ban and the consequential replacement of ICEVs with EVs could induce potential benefits such as decreasing air pollution, increasing usage of RES to meet the increased electricity demand of the transport sector, and decreasing greenhouse gas (GHG) emissions related to road transportation.

In 2019 in the UK, 79,747 licensed ultra-low emission vehicles (ULEVs) were registered. ULEVs include BEVs and PHEVs. These ULEV registrations represented 2.7% of all new vehicle registrations. ULEV registrations increased by 26% compared to 2018 (Department for Transport, 2020). Of all the ULEVs registered in the UK by 2019, 53% were PHEVs and 39% were BEVs. Not only is there an increasing share of EVs in the total vehicle fleet, the share of BEVs within EVs are also increasing. The share of new vehicle registrations which are electric is increasing, with diesel and petrol decreasing (Figure 1.1: adapted from Statista (Statista, 2021b)). New registrations of BEVs in 2019 were 140% higher than 2018, whereas PHEVs were 16% lower. In line with EV adoption, the number of charging points are also increasing. There are over 30,000 charging connectors in the UK, of which 7,750 (25%) are in London (Zap Map, 2020).

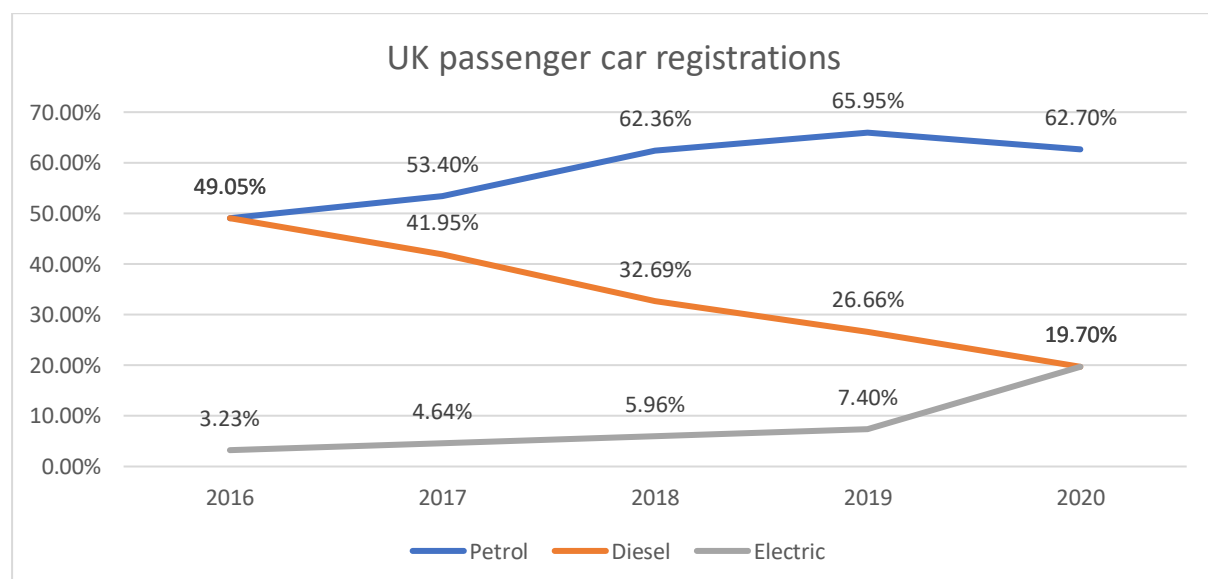


Figure 1.1 Passenger car registrations in the United Kingdom between 2016 and 2020, by fuel type (Statista, 2021b).

There are benefits of EV adoption, including decreasing pollution, RES to replace fossil fuels, greater RES utilization, decreased GHG emissions, and greater sustainability (Schuller *et al.*, 2011; Han *et al.*, 2013; Wang *et al.*, 2014; Energy UK, 2016; Nunes, Figueiredo and Brito, 2016).

Despite the wide range of potential benefits, EV adoption can also cause systemic challenges. EV adoption creates additional demand on the energy system. The energy needs of personal transportation will require electricity as the fuel, instead of fossil fuels. By 2035, EVs could account for an additional 14 TWh/year of energy demand in the UK (Energy UK, 2016). If this increased energy demand is met with an uncontrolled charging system of EVs, it can lead to increased stress on the grid (Peças Lopes, Soares and Rocha Almeida, 2009; Qian *et al.*, 2011; Van Vliet *et al.*, 2011; Weiller, 2011; Sundström and Binding, 2012; Shaukat *et al.*, 2017). A 20% penetration of EVs in the UK would lead to 35.8% increase in energy demand (Qian *et al.*, 2011). As well as increasing the total energy demand, EVs can affect the peak power demand within a day significantly, putting a stress on the energy infrastructure, with significantly higher power requirements at peak times (Peças Lopes, Soares and Rocha Almeida, 2009).

The increase in stress on the grid can be alleviated through coordinated charging (smart/controlled charging). Smart charging manages the load from EVs so that grid operations are protected and enhanced, whilst ensuring the EV users' charging requirements are met (Daina, 2014). As opposed to uncontrolled charging which charges when plugged in until fully charged, coordinated charging optimizes time and power of charging (Nunes, Figueiredo and Brito, 2016), and can aid in alleviating the peaks in energy demand.

Adoption of EVs also creates challenges to the EV users. Users must adapt and change their behaviour and thought process when fuelling their vehicles, due to the differences between EVs and ICEVs in operations and fuelling: petrol vs charging stations. These challenges could deter and diminish EV adoption. Thus, a tool helping EV users navigate the existing fragmented information on charging and complexity of charging scheduling would facilitate adoption of EVs by removing a major barrier.

One of the challenges faced by EV users is the need to consider an increasing amount of information in making their charging decision. This includes locations of EVSE at which to charge, different prices by location, time, and charging service provider (CSP) and ensuring the State of Energy (SoE) of the EV is enough to meet mobility needs at all times. A simple decision is to charge as much as possible at any available point. However, this may mean the user is paying more than if maximising charging at

cheapest locations. These variables create a convoluted system for an individual to consider at short time resolution, with shorter leniency on error, and higher frequency of charging needed due to smaller ranges of EVs compared to ICEVs. Even if individuals would try to plan carefully, it would be a strenuous task to perform every day, and humans are not entirely logical even in possession of enough information to be so (Latinopoulos, Sivakumar and Polak, 2017).

A part of this complexity, and impacts thereof, are pointed out in the context of taxi drivers specifically, but applicable to all EV users: taxi drivers without access to information of available charging stations can lose time, and thus potential earnings, by having to wait for a free charging station, or find another (Tian *et al.*, 2016). The root of the problem is the same for all EV users; that charging the EV has very different time costs to fuelling ICEVs. A tool that could help EV users navigate the existing fragmented information on charging could aid adoption of EVs.

1.1.2 Components of the evolving energy system

The energy system is expected to change in several ways in the near future. The changes will be at both system level and at individual consumer level. This subsection will describe and define these changes, and the changes will be linked to EVs in Subsection 1.1.3. These changes include the projected increase in electricity demand in the UK. The increase is dominated by the residential and commercial sectors, with demand from transport also projected to increase (Energy UK, 2016). Another change is that RES generation is expected to increase. Further changes through new technologies include adoption of demand side response (DSR), distributed energy resources (DER), battery energy storage system (BESS), smart meters and real-time, or temporally varying, energy tariffs at residential level. Real-time tariffs can give prices by every hour or half-hour and is referred to as dynamic Time-of-Use (TOU) tariff. These changes will make the energy system much more flexible, with synergies between the different components in the system. This is different to the current household energy system which simply draws the necessary energy demand from the grid. The adoption of these technologies at the individual level can lead to a much more symbiotic, albeit complicated, energy system for individuals. EVs are also part of this complex and evolving system.

1.1.2.1 RES

RES are expected to contribute an increasing proportion of global energy supply. Global photovoltaic (PV) generated energy capacity has risen from 25GW in 2009 to 175GW in 2014 (Energy UK, 2016). RES generation in the UK is forecast to increase from 126TWh in 2020 to 189TWh in 2040, representing

an increase in the share of total power generation from 42% to 56% (Department of Business Energy & Industrial Strategy, 2020). In 2019, 35.8% of UK's electricity was generation from renewables, led by wind power, bioenergy, PV panels, and hydropower (Department of Business Energy & Industrial Strategy, 2019). There is potential synergy between RES and EVs. For example, using EVs (and their ability to store energy) together with solar RES to supply a building's energy could reduce energy consumption from the grid by up to 68% (Alirezaei, Noori and Tatari, 2016).

1.1.2.2 DER

Distributed energy resources (DER) are energy sources distributed throughout the system, such as "stand-alone distributed generation units, storage system (e.g. heat pumps, batteries), solar thermal systems etc." (Energy UK, 2016). DER adds to the decentralisation of the energy system. DER present wider availability of potential interactions between EVs and the energy system (DER), than between EVs and traditional centralized generation. The wider availability comes from the fact that DER are often physically closer to individual EV users. DER generation is forecasted to increase from 21GW in 2020 to 28GW in 2035 (Energy UK, 2016). Many DER technologies are RES, thus, there is an accompanying increase.

1.1.2.3 DSR

Demand side response (DSR) is an energy management system which aims to shift energy demand by magnitude or time, to help reduce peak demands on the energy system. Certain energy uses, such as boiling water, or charging EVs could be done with some flexibility at times of low demand on the grid. EVs relate to DSR by their ability to charge at an alternative time, thereby shifting the energy demand temporally. For utility operators or Smart Building Operators (SBO), avoiding peak electricity prices for buildings can be significantly financially beneficial as price spikes can rise to several times higher than normal prices; in Texas electricity market, spot prices can reach as high as \$3,000/MWh which is magnitudes higher than usual prices (Zhang and Li, 2017).

1.1.2.4 BESS

Residential battery energy storage systems (BESS) are another interesting element of the evolving energy system. The storage capacity of BESS can aid the energy system by allowing individual residential units to store energy. The store energy can then be used at times of higher demands on the grid, which helps decrease the stress on the grid. Furthermore, they provide an outlet for storing excess RES from DER at individual residential units. Powervault (a company selling BESS) has partnered with EDF Energy to provide BESS to consumers, with the option to opt in for EDF Energy's grid services for a discount on the cost of the BESS. UK Power Networks trialled BESS for homes using Powervault, and due to the success of the initial trial is extending the scheme in South London (Department for

Business Energy & Industrial Strategy, 2020). This example showcases the potential of BESS in real world applications.

With the increase adoption of technologies in the evolving energy system, such as DER, BESS, RES, EVs and DSR, there is an opportunity to create an energy system where these components can collaborate (Clement-Nyns, Haesen and Driesen, 2011). The inclusion of EV, BESS and PV was found to remarkably increase the effectiveness of household energy management system (HEMS) with higher self-consumption potential (Duman *et al.*, 2021). A study based in Japan in 2018 found that a household connected to an EV and PV could lead to reducing electricity cost by 68%, and a 92% decarbonization of household energy system by 2030 (Kobashi and Yarime, 2019). Furthermore, such a system was already cost competitive with the use of grid electricity and a gasoline vehicle. The peaks in demand could be alleviated and RES generation fully utilised, through local storage and EVs as Mobile Energy Storage (MES) with timely DSR in buildings. Average UK residential PV installation is predicted to be 3.25kW in 2030, with 3.5% of all households being PV prosumers in 2030 (European Commission, 2017b). This installed capacity represents only around 8% of the technical potential for the UK. The leading countries in the report for uptake of PV in households are Netherlands (9.5%), Belgium (8.2%), Denmark (6.8%), Italy (5.9%) and Germany (5.8%). Kaluza, an OVO company, has developed technology that connects and controls domestic devices, smart heaters, EV chargers and domestic BESS in a smart way. They have trials to charge 300 EVs smartly in the UK, and a partnership with Powervault to utilise domestic BESS.

There are challenges for the various stakeholders in the adoption of these technologies. Governments face challenges providing informed policies to aid in adoption and operation of these technologies. Businesses including suppliers of products, energy providers and charging service providers face challenges adopting the right business model, and in communicating appropriately their business proposition and added value to consumers. Individual users face challenges in having the knowledge of the extent of benefits for them should they invest to install these systems. Quantitatively analysing the extent of benefits of integrating these different components of the evolving energy system would aid in informing these different stakeholders.

1.1.3 Interaction and integration of energy and mobility for individuals

The above-mentioned changes in the energy system allows interactions between BEVs and the energy system, even at the scale of individual residential houses and EV users. These interactions are enabled by the energy storage capability of BEVs and their ability to act as MES. There are different

configurations of the system possible for individual users, with synergies between the components of the system. These interactions and synergies could provide benefits to both users and the system.

Vehicle-to-home (V2H) allows vehicles to discharge to the home. Through this, vehicles can supplement residential energy demands by using energy imported in from public charging, or otherwise had been stored in the BEV.

Home-to-grid (H2G) allows energy to be exported from the home to the grid at an income for the residential home unit. This is also referred to as feed-in-tariff in the UK. These are mostly used by individual households to sell PV generated energy back to the grid. It also enables residential units with BESS to sell the stored energy. It is also possible for EVs to sell its stored energy through V2H then H2G.

Vehicle-to-grid (V2G) similarly allows EVs to supply energy to the grid, which can help the grid at times of high demand. This exporting could be done in public places (not at home). There are pilot studies being run to study their impacts, and how the operations could be managed (Mitsubishi Motors, 2017; Pearre and Ribberink, 2019).

There is potential to generate income or reduce cost by discharging to the grid through V2G, V2H, vehicle-to-building (V2B) and home-to-grid; collectively vehicle-to-home-to-grid (V2H2G). All these different options, information, and at short time resolution creates a very convoluted set of information for an individual to process and make charging decisions.

There are studies that have analysed the interactions of EVs with the energy system at various scales, with various configurations. The ability of BEVs to peak shave at a residential scale was studied (Khemakhem, Rekik and Krichen, 2019). Studies have analysed potential benefits of PV interactions with EVs at a nanogrid scale PV (van der Meer *et al.*, 2018) and system level scale (Nunes, Farias and Brito, 2015; Szinai *et al.*, 2020). Effects of combining PVs and BESS at individual household scale (Erdinc, 2014; Wu *et al.*, 2017; Doroudchi *et al.*, 2018; Hafiz, De Queiroz and Husain, 2019) and nanogrid scales (Kuang *et al.*, 2017; Salpakari *et al.*, 2017; Novoa and Brouwer, 2018; Barone *et al.*, 2019; Dagdougui, Benchrif and Ouammi, 2019; Domínguez-Navarro *et al.*, 2019) have been studied to varying degrees of configuration completeness, and from the focal point of different stakeholders. However, it was noted that few studies in the literature have analysed systems with PV and EV at a household level (Kobashi *et al.*, 2020). The household level would enable placing the focal point around individual BEV users, and thus analyse the extent of benefits for individual users, based on their mobility and BEV charging needs. The focal point of individuals should analyse the potential benefits of interactions of the BEVs with their residential household building, whilst optimising the energy flow and charging

scheduling of the BEV in public and at home. Including the interactions between the BEV and household in the analysis would involve integrating the flow of energy between the BEV, residential PV, and BESS, whilst meeting the residential energy demand.

The scope in this research will focus on individual households. The households may be rented or owned properties. The households are characterised by the number of occupants. Commercial buildings and facilities are not in scope of this research, as the focus of this research is on assessing the extent and distribution across society of the potential financial benefits of optimized energy management for individual users. Thus, the most appropriate building types of focus on are individual households.

1.1.4 Distribution of benefits across society

There are potential benefits from the adoption of BEVs, and the aforementioned interactions with the energy system, and synergies with different technologies. Analysis of the distribution across society of these benefits are important. This analysis is important in studying how the benefits could be distributed across the user population, based on demographic characteristics of the users. This would enable studying the extent of benefits, how the benefits vary across different types of users, and the equity of the distribution of the benefits. Understanding a potential differential distribution of the benefits is important as Evensen *et al.* stressed that there could be uneven financial costs of low-carbon transitions across demographics (2018). Low-income households (LIH) in the US spent \$1.23 per square foot on utilities compared to \$0.98 for all other households according to the American Housing Survey conducted by the U.S. Census Bureau (Drehobl, A., Ross, 2016). High income households were more likely to have energy efficient household appliances which can contribute to reducing energy bills (Xu and Chen, 2019). Smart meter prevalence was found to increase with income, with 18.0% for LIHs and to 26.8% for HIHs according to Residential Energy Consumption Survey in the US (Xu and Chen, 2019). Furthermore, it was suggested that people without smart new world energy services could become the new fuel poor, and it is hypothesised they are more likely to be those who are already financially worse off (Sovacool, Lipson and Chard, 2019).

There was a lack of studies in the literature that quantitatively analysed the distribution across the population of potential financial benefits of BEV operations and synergy with the energy system. Studies pertaining to the topic analysed the impacts of socio-economic and demographics characteristics on BEV load profiles (Fischer *et al.*, 2019), and discussed some policy implications (Noel, 2017; Noel *et al.*, 2017). The policies recommended (Noel, 2017) were more geared towards outlining

the main aims of what policies should do, as opposed to recommending specific actionable policies with details.

The discussion of the literature on analysis of the distribution of the benefits across society is covered in greater depth in Section 2.3.

1.2 Aims & Objectives

The main aim of this research is to explore the benefits, implications thereof, and the equity of distribution of these benefits to users across demographics. The benefits being explored are based on integrating in a holistic manner an individual BEV user's mobility and energy system and optimizing the individual's energy management and charging schedule based on their travel itinerary. The integrated energy system environment in this study will encompass the BEV, V2H2G, residential energy demand, residential BESS, and PV generation.

This exploration of benefits could inform important stakeholders in BEV adoption. These stakeholders could be informed on different functions. These include governments in policy making. Policy making that can be informed include BEV adoption, and equity across society of the distribution of the benefits of BEV adoption. Furthermore, businesses such as suppliers of energy system components, energy providers and charging service providers could be informed on adopting the right business model, and in communicating appropriately their business proposition and added value to consumers.

To achieve the research aim, two research objectives (RO) need achieving. The ROs will be achieved in the context of a case study in London by using London Travel Data Survey (LTDS) data. The two objectives are:

- RO1: Develop a conceptual framework and DST to navigate the complexity of charging scheduling and energy management within the integrated energy system.
- RO2: Generate insights regarding the extent and distribution across society of the potential financial benefits of optimized energy management for individual users. To gain insights on how the benefits are affected by the parameters of BEV interactions in an integrated energy system (such as access to H2G, or price of electricity).

To achieve the objectives, several tasks must be accomplished. Figure 1.2 shows the tasks necessary to achieve the aim of this research by achieving the two ROs. The tasks need accomplishing in the research in the sequence presented. The tasks are discussed in further detail directly below.

These ROs and tasks aid in answering the research questions (detailed in Section 2.4), and policy questions (detailed directly after the tasks). The ROs and tasks also aid in verifying hypotheses to the research questions; these hypotheses are set out in Subsection 3.4.1.

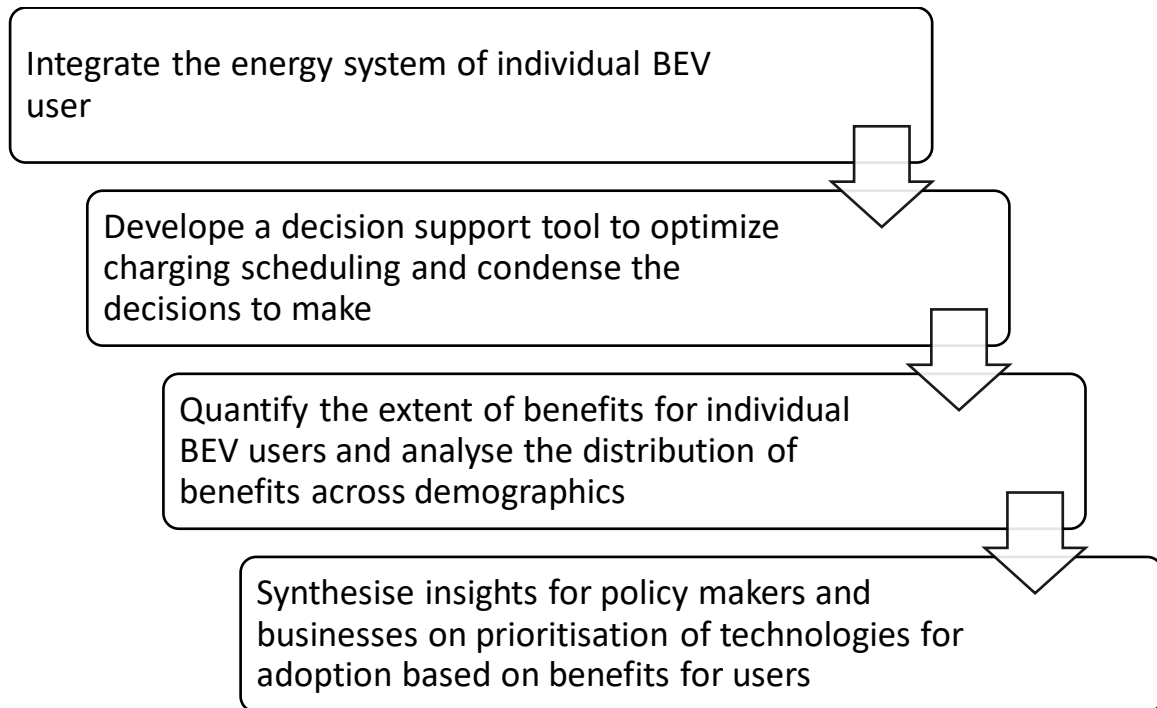


Figure 1.2 Sequence of tasks to be achieved to accomplish the research objectives and aim of the research.

The tasks are:

- T1: Develop a conceptual framework for an integrated system of the total energy needs of an individual BEV user. This framework includes the user's travel and residential energy needs and integrates the BEV with the residential home via V2H2G, residential energy demand, BESS, and PV. The travel needs will be based on travel itineraries detailing each trip. The detailing of each trip enables opportunistic charging decision making.
- T2: Develop a decision support tool to assist BEV users navigate the convoluted set of information to consider in making charging scheduling and energy management decisions of the integrated system. Developing the tool is achieved by formulating the optimization problem to minimise an individual BEV user's energy cost of fulfilling their mobility needs with interactions with their integrated energy system.
- T3: Analyse the financial benefits, and implications thereof, to BEV users and distribution across demographics, of an integrated energy system. To achieve this, develop an analytical

framework. The analysis is based on the results of the optimization, and the different variables of user characteristics and scenario parameters.

- T4: Provide insights for policy makers and businesses to inform their approaches in adapting to BEV adoption.

1.3 Contributions

The contributions of this research are in answering the research and policy questions regarding the extent and distribution of benefits to users and society through optimising the scheduling of energy flows between the BEV, grid, home, residential BESS, and PV. They are summarised as:

- Quantitative analysis and implications of financial benefits of individual BEV users optimizing their charging scheduling and energy management with V2H2G, residential energy demand, PV, and BESS. Quantitative analysis of the effects of user travel pattern characteristics and technology parameters on the financial benefits.
- Quantitative analysis and implications of the equity of distribution of the financial benefits across demographics.

There were some gaps in the literature noted regarding the first contribution. Studies that analysed the relationship between technology parameters (for example size of BESS) with the extent of benefits were not focussed on individual users, nor did they include the optimization of public charging of the BEVs (Erdinc, 2014; Wu *et al.*, 2017; Domínguez-Navarro *et al.*, 2019). Studies also did not include the energy demands of the building to analyse the relationship between extent of financial benefits with the technology set up and travel pattern characteristics (Erdinc, 2014; Wu *et al.*, 2017; Doroudchi *et al.*, 2018; Hafiz, De Queiroz and Husain, 2019). Studies that analysed the energy interaction BEVs have with the energy environment only considered a subset of the components to be analysed in this research (Nunes, Farias and Brito, 2015; van der Meer *et al.*, 2018; Khemakhem, Rekik and Krichen, 2019; Szinai *et al.*, 2020). Whilst there are several studies looking at optimization from the perspective a microgrid or larger scale (Nunes, Farias and Brito, 2015; Kuang *et al.*, 2017; Salpakari *et al.*, 2017; Novoa and Brouwer, 2018; van der Meer *et al.*, 2018; Barone *et al.*, 2019; Dagdougui, Benchrif and Ouammi, 2019; Domínguez-Navarro *et al.*, 2019; Szinai *et al.*, 2020), studies on individual residential homes were lacking. Previous studies analysing policy implications (Noel, 2017; Noel *et al.*, 2017) were based on systems level rather than based on analysis, or geared towards individual users level.

The problem formulation in this research is generic, and can therefore readily be extended to a larger scale, or replicated for different case studies, as with previous studies in which their contributions were also the adaptability of their models (Salpakari *et al.*, 2017; van der Meer *et al.*, 2018). Analysis in this thesis is in high time resolution, as it was stated that previous studies used coarse time resolution (Salpakari *et al.*, 2017).

The methodology used is fit for purpose. Linear programming (LP) is used in this research. There is precedent of LP and mixed integer linear programming (MILP) being used in previous studies that also sought to optimize energy flows in an integrated system (Erdinc, 2014; Kuang *et al.*, 2017; Salpakari *et al.*, 2017; Doroudchi *et al.*, 2018; van der Meer *et al.*, 2018). CPLEX was used to solve the optimization. Previous studies have also used CPLEX (Erdinc, 2014; Salpakari *et al.*, 2017; van der Meer *et al.*, 2018).

This research presents quantitative extents of benefits for individual users across almost 1,500 different scenarios. Furthermore, the results can guide the type of technologies that are most beneficial for different types of users, based on their travel pattern characteristics. The basis around user travel pattern characteristics can aid individual users make an informed choice on the technologies to invest in considering the capital cost, knowing that the benefits calculated were based on specific travel pattern characteristics. Policy makers can be aided on the technologies that should be prioritised for adoption, based on the relationship between extent of benefits and technology parameters, and impacts of different energy system configurations of individuals. Businesses can also be better informed from the findings of this research to adapt their business models appropriately to BEV adoption.

The second contribution from above is the more significant contribution, addressing the bigger gap in the literature. This contribution of this research is in quantitatively studying the distribution of benefits across demographics, and implications for policies. The lack of studies, both qualitative and quantitative, addressing the issue of equity and justice of EVs and V2G was highlighted (Sovacool, Kester, *et al.*, 2019a), noting that access to EVs and V2G could be only for the rich. A gap in the literature was noted of the lack of studies that have quantitatively analysed the differential distribution across society of the extent of financial benefits for individual users of optimized energy management of BEVs integrated with V2H2G, residential energy demand, PV, and BESS. The gap regarding the quantitative analysis of the relationships between demographic characteristics of users and the extent of financial benefits was noted. A relationship between demographic factors and BEV charging profiles was shown (Fischer *et al.*, 2019), which suggests that the distribution of financial benefits of the adoption of these technologies and the usage of a decision support tool (DST) may not be equitable across society. There could be uneven financial costs of low-carbon transitions (Evensen

et al., 2018), and uneven benefits due to uneven uptake of smart new world energy; it is hypothesised they are more likely to be those who are already financially worse off (Sovacool, Lipson and Chard, 2019). These arguments stress the need for a novel quantitative analysis of the distribution of financial benefits to individuals across demographic factors.

The significance of this research is in showing insights on equity of distribution of financial benefits, using London as the case study. The insights on the relationship between extent of benefits with income levels, geographical location, and household sizes can inform policy makers.

The main contributions to society and potential impacts of this research are:

- Informing on the equity of distribution across demographics of the financial benefits of BEV adoption.
- Easing operation of BEVs for individual users through the development of a DST which can condense the amount of information they must consider in charging scheduling.
- Informing on the potential synergy of integrating BEV, V2H2G, residential energy demand, BESS, and PV.
- Tailored recommendations for BEV users of the technologies that would be most financially beneficial for them to adopt, and the equity analysis thereof, based on their characteristics
- Providing insights for businesses, policy makers, and governments of the impacts of effects of BEV specifications and different integrated energy system environment parameters.

1.4 Thesis outline

The thesis is structured into seven chapters:

Chapter 2 reviews the literature of the fields of interest of integrating BEV with V2H2G, residential energy demand, residential BESS, and PV. The literature into the equity of distribution of the benefits of the changing energy system is then reviewed.

Chapter 3 details the methodology used in the research. It outlines the analytical framework used, the conceptual framework that integrates the BEV operations, V2H2G, residential energy demand, BESS and PV, and the regression analysis approach for analysis of the results.

Chapter 4 outlines the formulation of the optimization problem, and the design of different scenarios of integration and technology setup to be solved by the optimization problem. The results from the different scenarios allow the analysis of effects of the various variables representing the technology

setup, which are varied as scenario parameters. The assumptions made for the design of the environment and the methodology for solving the optimization are detailed here.

Chapter 5 details the data and parameters used for the optimization, including data collection, pre-processing, and assumptions.

Chapter 6 discusses the results of the optimization, their analyses, and discussions.

Chapter 7 concludes the thesis by providing a summary of the previous chapters and highlighting the key conclusions and contributions. Potential future works are then detailed.

Chapter 2

State of the art of an integrated energy system environment of a BEV user, and the benefits for users

The general context within which the research sits was discussed in the previous chapter, followed by the aims and objectives of the research.

It is desired to better understand how BEVs could integrate into and interact with the changing energy system, particularly the changes relevant to individual users such as residential BESS and PV. Better understanding the BEV integration would allow studying what the challenges and potential benefits are to individual users and to the wider context stakeholders. There is a need to better understand the potential solutions to challenges for individual BEV. Furthermore, understanding the distribution of potential benefits across demographics is desired. To that end, a review of the literature of systems integrating BEV charging operations with V2H2G, residential and building energy demands, BESS and PV, and optimal operations of such systems was conducted. A review of the literature on systems that aimed to aid individual BEV users was conducted. The literature on distribution of benefits and costs of the energy was then reviewed. The purpose of this chapter is to review the current aforementioned literature and identify significant research gaps for further investigation to be addressed by the research in this thesis.

Section 2.1 reviews systems to aid individual EV users, and the usage of optimization for charging scheduling of EVs. Section 2.2 reviews the integration of EVs with the wider energy system via V2H, H2G and V2G, with building energy demand, energy storage and PV generation. Section 2.3 reviews studies on the distribution of costs and benefits of energy systems across society. Section 2.4 summarises the findings of the literature review, and the gaps identified in the literature. The gaps identified aided in defining the contributions of this research (Section 1.3).

From the identified gaps and motivation of the research, the proposed analytical and conceptual frameworks are detailed in Chapter 3, and the construction of the problem formulation in Chapter 4.

2.1 Optimisation of charging scheduling of individual EV users based on detailed full day travel itinerary considering their complete energy needs

The adoption of BEVs presents a challenge for users in making charging decisions. BEVs have lower ranges than ICEVs. Therefore, users must consider different factors in fuelling their car in a shorter time frame and more frequently. The different factors to consider include the available locations of charging points, different prices by location and charging service provider (CSP) and ensuring adequate battery state of energy (SoE) levels to meet their mobility needs. Whilst the factors to consider are very similar to fuelling ICEVs, the shorter time frame with many variations to consider creates a challenge. This can lead users to adopt a simplistic “dumb charging” approach (charging as much as possible wherever possible with no consideration to price differentials), which can lead to non-optimal charging costs. Decision support tools (DST) helping BEV users to make charging decisions can ease this challenge. DSTs could also provide financial benefits to BEV users by reducing their charging costs. DSTs can aid in tackling a barrier to BEV adoption, and thereby enable gaining other benefits for society, such as lowering urban air pollution and fuelling travel energy demand with renewable energies. It is important to identify how the existing studies have attempted to aid individual users. Therefore, in-depth review of the literature of DST studies are focussed on 2 areas: 1) on those with the perspective of the individual user of the DST, and 2) identifying how studies where individuals were not the focus could be extended to change the focus to be on the individual perspective or adapted appropriately.

Studies presenting DSTs for individuals (Ferreira *et al.*, 2011; González *et al.*, 2014; Cardona, López and Rider, 2018) could be extended to further the solutions presented for optimal charging scheduling for individuals. A study for individual users presented a recommender system (or a DST) for EV users based on their mobility needs (Ferreira *et al.*, 2011), however, the study did not look into how the charging scheduling could be optimized. Nor did the recommender provide guidance on how much to charge at each location. An analysis of scheduling of EV charging based on mobility needs of the user from the perspective of each EV was presented (González *et al.*, 2014), using generated schedule for a weekday. The schedule was used to optimize the charging of users. The price was based on hourly pricing, rather than location specific pricing; this study could be extended in this aspect to add more realism and account for the variability in prices users have to consider in the defragmented CSP market. The study discussed the results in terms of proportion of journeys which EVs would be adequate for fulfilling and therefore be suitable in replacing ICEVs. There was no analysis of the actual financial benefit for individuals. Nor was the interplay with the wider energy system through V2B or V2G

considered. This study could be extended in these aspects. A decentralized approach for EV charging coordination (Cardona, López and Rider, 2018) took into account the historical route of EVs, but only calculated the minimum amount of energy as a proportion of the full EV battery as a threshold at which the users require immediate charging. There was no analysis of the full day itinerary of the mobility needs to calculate the optimal charging amount at each location.

Further to the gap in the literature regarding analysing with the focal point of individual users, studies that have analysed the charging operations of EVs (with any perspective, such as individuals, EV aggregator, or EV fleet operators, or buildings) tended to significantly simplify the travel itineraries of EV users. Examples of simplifications include only considering commuting to work trips and excluding other types of trips, taking overall trip loads, or not looking at each trip (Alirezai, Noori and Tatari, 2016; Kasturi, Bhoi and Nayak, 2021; Muthiah-Nakarajan *et al.*, 2021; ur Rehman, Yaqoob and Adil Khan, 2022), and assuming states of energy (SoE) or charging demand, rather than explicitly calculating the SoE from travel patterns (González *et al.*, 2014). It was pointed out that few works in the literature were concerned with multi-trips per day when considering EV charging demand and availability for interaction with the home (Abdelaal *et al.*, 2021). That study did add in the element of multi-trips per day. However, it did not include charging in public as part of the model. The multi-trips in that study could be interpreted as simply time constraints on availability of EV interacting with the residential home. Furthermore, the two trips considered had set times and distances. There was no consideration of travel pattern variation across users. Extending on these studies by using more detailed travel itineraries could add greater meaning and realism to the analysis of the results and discussions. The importance of accurate travel itineraries when analysing energy demand of EVs and interactions with the wider energy system was noted in previous works (Green, Wang and Alam, 2011; Jian *et al.*, 2015; Salpakari *et al.*, 2017; Wu and Sioshansi, 2017; Muratori, 2018). Less uncertainty of EV arrival times and energy demand would lead to a better centralized EV charging control model (Wu and Sioshansi, 2017). The estimation of total PEV charging requirement from average daily vehicle miles travelled and average fuel economy was pointed out as a limitation of current studies (Muratori, 2018), and that more detailed information would allow for more insights to be gained, such as consumption and peak demand of PEV charging on the electric system. A difficulty with using EVs as energy sources arises due to the uncertainty in availability of EVs due to their mobility; where they will be at what time is uncertain (Jian *et al.*, 2015). A study identified driving patterns as a key factor on impacts of EVs on the distribution network (Green, Wang and Alam, 2011), but used average miles driven during a day, and random locations of EVs during charging events to capture the impact of driving patterns. The energy demands for PEVs were derived from travel survey statistics using inverse transform

sampling of cumulative distribution functions, rather than travel survey itinerary as input (Salpakari *et al.*, 2017).

Some studies did use real travel data, but the way the data was used, and incorporating it into a system to aid individual users could be extended. Real travel data was used to create PHEV charging load profiles (Darabi and Ferdowsi, 2011). However, the approach taken could be extended. The approach took the end travel time of the day, rather than considering the details of each trip. Each trip, and charging at each trip, within the day's travel itinerary was not considered. The daily vehicle mileage and the energy demand was calculated simplistically from the annual driving mileage divided by 365 (days in a year). This study did not analyse from the perspective of an individual who could optimize their charging scheduling. Historical routes of EVs were used (Cardona, López and Rider, 2018), but only to calculate the minimum amount of energy as a proportion of the full EV battery as a threshold at which the users required immediate charging. The charging demand of EVs temporally was analysed from 2000-2001 California State-wide Household Travel Survey (Kang and Recker, 2009). This study used each trip in a day's travel survey to determine the time of demand by calculating travel distance; the concepts in this study can be adapted to the wider context of optimizing charging scheduling for EVs. The derivation of arrival and departure of EVs was a key component in determining the EVs' residence at the V2G station and therefore the availability for V2G (Gough *et al.*, 2017), and the concept will extend to charging decisions for EV users. These studies highlight the need to use detailed real travel data in analyses involving EVs.

In addition to the lack of studies where the focal point was for individual users using real travel data, there was a lack of studies that applied charging scheduling as decision variables which could be used to aid individual users, for example in the form of a DST. The literature review on EV charging behaviour yielded studies using travel data, however, not with charging as an operational aspect for an individual EV user, or in an integrated energy system (Wolinetz *et al.*, 2018; Kim, 2019). These studies used different charging scenarios such as accumulated end of day residential charging, and charging at every public opportunity, however, the potential to aid users with charging decisions was not analysed. Similarly, another study considering charging demand from EVs (Kim and Rahimi, 2014), to consider an optimal operating cost for EV users also did not guide users with charging decisions. A study that analysed the benefits for EV users of charging at opportune times and prices on an hourly pricing program with charging scheduling (Zethmayr and Kolata, 2019) was not from the perspective of an individual. The scheduling of charging in this study was not realistic in considering the mobile nature of an EV. The required charging was allocated pro rata to the ranked hourly slots in a day based on price until the total charging amount was fulfilled, not considering that EVs are not parked at all times.

The literature review on systems to aid individual users, such as through optimizing charging scheduling decisions for users yielded several gaps which could be extended. These include studies where the focal point was around individual users, studies where the charging scheduling at each trip were decision variables could be extended, and the usage of real travel data, whilst being highlighted as being important, could be extended.

2.2 Integration of EVs with the wider energy system via V2H, H2G and V2G, with building energy demand, storage, and PV generation

The optimization of charging scheduling of EVs can increase the benefits of EV adoption for users. Furthermore, there are further benefits from the different changes afoot. Namely, EV adoption, the changes in the energy system of greater and more widespread BESS and PV capacities, and the interactions these can have with each other through V2H2G, can provide further benefits. Synergetic benefits may exist, with the overall benefits greater than the sum of benefits from the individual changes. These synergies may be attainable through integrating these different changes under one system. In this context of beneficial changes, optimizing for this integrated system can increase the benefits, including the synergetic aspect. The literature on the above aspects is reviewed to identify how previous studies have attempted to provide solutions and is presented in this subsection.

Some aspects were lacking and could be extended in studies that analysed an integrated, holistic system of EVs and energy system from the perspective of individual EVs, using detailed travel patterns including data for each trip. These aspects are further detailed in this subsection. The frameworks did not capture holistically in enough detail the different components that make up a system for an individual. This included displacing either of charging at home or public out of scope of studies and only optimised for one of those. This exclusion of either public or home charging meant the costs of the excluded charging would be incurred by the user anyways if applied in reality, but non-optimally. Another aspect which could be extended is the lack of analysis involving charging decisions for each trip in an analysis of an individual's full day's travel pattern using real travel data.

Similar to the literature reviewed in Section 2.1, much of the literature focused on the integrated system with the focal point of an energy or EV aggregator, EV fleet operators, or building management. This simplified EVs as merely additional energy load that arrive at buildings, (Wi, Lee and Joo, 2013; Alirezaei, Noori and Tatari, 2016; Gough *et al.*, 2017), or somewhere the EV storage capacities were used to benefit the building operators rather than individual users (Wu and Sioshansi, 2017; Ferro *et*

al., 2018). In such studies, as the focus was building energy management, the transportation aspect could be improved by including in greater detail the travel itineraries of individual users, similarly to studies reviewed in Section 2.1.

Finally, whilst some studies did take a more individual focused approach, there was no analysis of the distribution across society of those benefits for different types of users and demographics. This aspect is further discussed in Section 2.3.

The literature on the integration of EVs with the grid via V2H2G and synergy with PV and BESS was reviewed in this Section. For greater detail, more specific reviews of the system are presented in the two following subsections. These subsections take the system and concepts thus far explored and reviews them in two separate categories. The review on the integration of EVs with the grid is presented in Subsection 2.2.1, and the review on the integration of the EV, the grid and PV and BESS in Subsection 2.2.2.

2.2.1 Integration with the grid

With increased EV adoption, there is potential for benefits from the bidirectional interactions of EVs with wider energy system; this can be with buildings (V2B) or the grid (V2G) or both (V2B2G). This integration could be managed with an optimal energy management system to increase the potential benefits. A demonstration of V2B involved Nissan Leaf connecting to a commercial enterprise to reduce building peak demand (Engerati, 2014). Barone *et al* (2019) analysed the literature and found that there was a great research effort toward the study of the EV operations within the grid, but only few studies on the V2H concept, such as EV integration energy balance of buildings with RES. This subsection reviews the literature of such interactions and identifies how the literature could be extended.

As EV adoption increases, the load from EVs should be integrated with load from buildings. Muratori pointed out that since PEVs are primarily charged at homes, the energy load of PEVs when considering the residential load can no longer be neglected (Muratori, 2018). Barone *et al* pointed out that only few papers analysed the energy demand of vehicles as building-related energy use, including the EV in the energy buildings' energy balance (2019). This could also be interpreted as the need to optimize the total EV charging costs, rather than only analysing either of public or home charging and displacing the other out of scope. The analysis of only one of public or home charging needs was seen in studies which took one of two approaches. Either, the approach focussing on an EV travelling throughout the day and deferring charging at home out of scope by considering the analysis finished once it had

reached home (Wu *et al.*, 2016). Or the approach focussing on a home (Wi, Lee and Joo, 2013; Munkhammar *et al.*, 2015; Alirezaei, Noori and Tatari, 2016; Abdelaal *et al.*, 2021) or building (Wu and Sioshansi, 2017; Ferro *et al.*, 2018; Thomas, Deblecker and Ioakimidis, 2018) to which EVs came and went, with an assumed state of energy. In these home or building focussed approaches, the analysis of public charging cost was excluded, with the aim being to optimize the building's energy use, whilst taking into account some of the synergies of the different components. If applied in reality, either approach could lead to pushing greater amounts of the cost to the excluded side, and unwittingly increasing the overall cost for a user if they are responsible for both the EV charging and building energy cost. Some studies were lacking on greater detail of the travel considerations of the EV users (Munkhammar *et al.*, 2015; Wu and Sioshansi, 2017; Thomas, Deblecker and Ioakimidis, 2018).

V2G is another form of interaction of EVs with the grid and has the potential to provide benefits to the energy system. However, there is uncertainty over its implementation and availability for retail customers. Shaukat pointed out the potential for V2G trading in electricity markets (2018), however, the relationship between vehicle use, building energy demand, and market requirement is relatively unknown (Gough *et al.*, 2017). V2G can provide potential economic and environmental benefits to the energy system with EVs acting as MES (Galv, 2004; Bozchalui and Sharma, 2012; Abdeltawab and Mohamed, 2017; Noel *et al.*, 2018; Thomas, Deblecker and Ioakimidis, 2018). Interestingly, from interviews with experts, more believed the benefits of V2G to be related to renewable energy integration and V2H, rather than the literature focused grid services (Noel *et al.*, 2018). However, V2G is not very well understood even among experts working with or around electric mobility, evidenced by a study in which only 23% of interviews with the experts could offer concrete policy related suggestions (Kester *et al.*, 2018). For EV users, questions of the range of EVs were found to be the most important determinants in V2G participation (Geske and Schumann, 2018). There are several issues that need to be resolved for V2G (Bhatti *et al.*, 2016). More advanced communications for charging systems are required for V2G. V2G and demand side flexibility of EVs go hand in hand, however, this was found to not be a priority for EV manufacturers, even though they believed EVs were well suited for it. Flexibility market is currently complicated and requires simplification to allow manufacturers to create a product for users (Earl and Fell, 2019). Demand side flexibility was regarded as having potential but requiring time.

Promisingly, there have been successful V2G demonstration projects, for privately and publicly owned EVs. The ACES Project (Across Continents Electric Vehicle Services) (Pearre and Ribberink, 2019) involves publicly and privately owned Nissan vehicles and V2G chargers to prove that EVs can be used for effectively balance the system. Mitsubishi will provide services for capacity reserve and balancing services through Mitsubishi Outlanders parked at home or at workplace (Mitsubishi Motors, 2017).

The project takes place in Amsterdam, where there are 25,000 Mitsubishi Outlander. Added economic value from V2G compared to smart charging was found to be possible (Payne and Cox, 2019), although the extent of the value was found to be highly variable on factors such as plug-in rate; this study involved both privately and publicly owned EVs.

Another interesting aspect of EV interaction with the grid is the advent of dynamic real-time TOU residential electricity tariffs. This can affect the cost of charging for EV users, as well as income from V2H2G. The affect comes from the temporally varying prices of electricity, where certain times are more expensive, or more profitable, than others. The adoption of half-hourly TOU tariffs still has many challenges. One of them is the difficulty in allowing consumers gauge the benefit of these tariffs, such as by the usage of price comparison sites (Carmichael et al., 2021). However, TOU tariffs can offer many benefits and is one of the technologies that form the future of residential energy ecosystems. Flexible power pricing was shown to reduce overall demand peaks (Schreiber et al., 2015). On the other hand, half-hourly tariff was found to offer little additional value to V2G above what can be captured from existing E7 tariffs (Payne and Cox, 2019). Hourly electricity day-ahead market prices was used in another previous study (Salpakari *et al.*, 2017). The lack of coherence in findings from these studies show the need to study the effects of such pricing in further detail, in more complicated systems and different scenarios. The study of impacts on users of using TOU tariffs becomes more important as these tariffs become more widely available.

2.2.2 Integration including PV and BESS

The energy storage capability of EVs present an opportunity for EVs to interact with the wider energy system via V2H, V2G, and H2G (allowing V2H2G). BEV interactions can also involve the energy demand of buildings, BESS, and PV. Specifically, for individual users, this could involve integration of the EV with the residential energy demand, BESS, and PV. Such integration would form the individual user's residential energy environment or ecosystem. The potential benefits for the wider system of this integration include increased utilization of RES and load balancing. Individual users have the opportunity to gain financially by decreasing their energy cost through the interactions, and also through the opportunity to sell energy to the grid when. How previous studies have integrated such systems are reviewed to identify how the literature could be extended.

There are multiple ways EVs could synergize with PV. Simplistically, the PV is an alternative source of energy for the EV users and could decrease energy cost by allowing less purchasing of electricity from the grid; this could also reduce GHG emissions. Beyond the PV being a simple source of energy, EVs can increase PV utilization by storing excess PV generation. This storage element of the interaction

could unlock additional potential of PV. The importance of RES coupling with BEVs in allowing BEVs to contribute to combatting climate change was highlighted by Priessner and Hampl (2020). The environment for EV and PV integration exists, even domestically, and for individual users. There are about one million households with PV installation in the UK (Strielkowski, Štreimikienė and Bilan, 2017). Small scale domestic solar PV, typically less than 4kW, is the largest sub-sector of the UK solar PV market, both in terms of number of installations and total capacity installed (Greater London Authority, 2018). Almost 75% of PV capacity in London was installed on domestic buildings, with average capacity 3.3kW (Greater London Authority, 2018). The potential benefits from such integration have been demonstrated. Residential PV could reduce total cost of ownership of BEVs by 50% in Hawaii (Coffman, Bernstein and Wee, 2017). PV self-consumption of up to 90% was possible depending on the system configuration (Good *et al.*, 2019; Gudmunds *et al.*, 2020). Gudmunds *et al.* (2020) specified the significance of the effect of V2H on PV self-consumption. Using EVs coupled with residential energy demand and solar RES, to supply a building's energy could reduce energy consumption from the grid by up to 68% (Alirezaei, Noori and Tatari, 2016). This study was based on residential homes, and it would be interesting to consider studies with BESS integrated into the system as well. Other studies were based on residential home energy system, but were also lacking BESS integration (Wu *et al.*, 2016; Ben Slama, 2021; Higashitani *et al.*, 2021).

Further synergy could exist by integrating a BESS with EVs and PV into one system. The impact of residential homes with BESS and PV integrated with EV charging was of particular interest. The literature on potential synergies of EVs with BESS and PV, residential energy demand and bidirectional energy flows at a single household level was reviewed, to understand how they could impact individual users, and the approaches taken in previous analyses. Benefits from synergy of EV, PV and BESS was highlighted (Hoarau and Perez, 2018). It was noted that few studies in the literature have analysed systems with PV and EV at a household level (Kobashi *et al.*, 2020). A home energy management problem aimed to minimize electricity purchasing cost of a single home, which had PV, BESS, and BEV charging needs (Yan *et al.*, 2020). This integrated energy system was of interest and presented the potential make up of homes in the near future. The optimization in this study took the focus of the home, and the EV element was dealt with simplistically, by simply requiring 80% of charge by 7am, and a 40km commute for work. There was no consideration of optimizing the charging of the EV whilst in public. Given that the objective was, in essence, to minimize the electricity cost for individual homeowners, there is scope for extending on this study. Firstly, the travel element of the problem could be extended by including more than just home-work commuting mobility needs. Secondly, by extending to consider the total electricity cost to the owner and including charging whilst in public in the optimization. The reason for the latter extension is because the public charging cost would

eventually have to be paid by the EV and homeowner, thus it would be important to add this element into such an analysis of an integrated system. Similar potential extensions as stated above could be applied to other studies of integrated systems (Chitsuphaphan, Yang and Dai, 2020; Wang *et al.*, 2020; Kasturi, Bhoi and Nayak, 2021; ur Rehman, Yaqoob and Adil Khan, 2022). Another study with home energy management system including BEV charging, H2G, PV and ESS for a single home to optimize drawdown from the grid and maximise on site generation use (Doroudchi *et al.*, 2018) also did not consider the public charging of the BEV in the optimization. The public charging element was also missing in a study of optimization of energy bill for a single home (Hafiz, De Queiroz and Husain, 2019).

A study combined an energy and charging model of PV, BESS and EV at the household level. (Scorrano *et al.*, 2020). This study included a full-fledged EV driving profile model and total cost of ownership (TCO) model, and this combination was cited as novel. It allowed investigating important research questions. Their findings could guide households in their purchasing decisions, car manufacturers and electricity providers in offering PV, BESS, EV bundles, and policymakers in accelerating the uptake of EVs and decarbonizing the transport sector. The study is very relevant to the literature of interest in this thesis. The study is current given the increasing possibility of households who could access simultaneously PV, BESS and EV. Therefore, investigating the financial impacts to individuals of adopting these technologies can yield important insights. In this study, the driving profile of a typical individual user was modelled for an individual year, splitting the year into various day types such as workdays and holidays. Rather than using real travel data, or a more varied simulation, the driving profile had set parameters for intervals for departure and arrival times and distances travelled for each of the day types, from which different mobility profiles were simulated by multiplying the intervals for an index. The approach taken in this study with respect to the travel pattern of EV users could be extended. The system of energy transfers between the PV, BESS, EV and the grid was structured with a set of hierarchical laws that dictated when transfers would take place. For example, PV charges the EV, and if the PV is not sufficient, BESS would supplement, and if the BESS was also not sufficient, the EV would draw from the grid. Seemingly, it was an overall net balance of supply and demand, rather than a system to schedule the actual optimal energy transfers in a more fluid manner. There were studies that integrated PV and EV at a household level with V2H and V2G (only whilst the EV was at home) (Lazzeroni *et al.*, 2019; Ian Adrian, Manjang and Kitta, 2020). These studies were similarly relevant and interesting. There is potential to build on these studies by adding in BESS and optimizing of charging of the EV whilst in public. Another study integrated PV and EV at a household level with V2H and V2G (only whilst the EV was at home) (Lazzeroni *et al.*, 2019). This study was similarly relevant and interesting. There is potential to build on this study by adding in BESS and optimizing of charging of the EV whilst in public. Another study integrated PV, BESS and EV at a

household level with V2H and temporally varying electricity tariff (Aguilar-Dominguez, Dunbar and Brown, 2020). It was noted in the study that no previous studies considered the demand from grid profile when the aim was reduction of consumer electricity cost, with different electricity tariffs, V2H, and taking into account EV availability. This study could be extended by optimizing the charging of the EV throughout its full travel itinerary, as the charging costs would contribute to the consumer's overall electricity cost, which was not in scope in this study.

A quantitative analysis of the economic viability of PV and EV or PV and BESS systems for residential households in Japan (Kobashi and Yarime, 2019), and Kyoto and Shenzhen (Kobashi *et al.*, 2020) highlighted the importance of and rising potential for linking PV with EV. Real travel survey data were used to calculate EV availability and average durations of the car being out of home to create a fixed energy demand profile to be met. Similar to previous studies, this study matched the demands and supplies of energy, and considered the economic viability of these systems, without optimization of the controllable decisions of charging and discharging of EVs or BESS. This study could be extended to optimize the energy management to guide users' decisions, to further the potential economic benefits accessible to individual households. The study could also be extended by considering a system of all of EV, PV and BESS. Similar extension of including all elements of EV, BESS, and PV could be made to another study (Higashitani *et al.*, 2021). That study focused its analysis on the performance of V2H systems and its profitability, rather than energy management guidance for users. That study discussed the scarcity of studies in the literature that have compared combining V2H and BESS against one of V2H or BESS. The study pointed out that there has been no comprehensive discussion of what types of households should adopt V2H systems, and whether they should be installed alongside a BESS. Furthermore, the study also highlighted that such information should be used to guide design of residential energy systems for the future, including interactions with EVs. It would be important to consider a similar notion of information which guides design of residential energy systems, but taking in aspects of which types of EV drivers would benefit from different setups of the energy system. That is, taking the focus around an EV driver's travel pattern characteristics rather than household type. A very recent study (Iria and Soares, 2020) presented an optimal configuration of PV, BESS (in terms of capacity) with BEV charging station for a single house in Portugal, aiming on optimizing the operation and annualized investment cost. The study focused on the perspective of a single house and its energy consumption, and the BEV consumption was regarded as an add on demand. However, there was no consideration of the public charging scheduling of a BEV. One of the tariffs for residential energy in the study was a 3-rate tariff across 6 periods in a day. The time horizon was 1 year at 15-minute resolution. They cite their contribution as the proposal of a new optimization model to plan the house of the future, selecting the optimal portfolio of smart home technologies and tariffs that minimize the

investment and operation cost of the homeowner. The study states that to their knowledge, none of the studies in the literature formulated such an optimization. The study can be very impactful for household owners in deciding the uptake of such technologies, and in adding to the literature of an integrated energy system for individual homes. A similarly novel study combined electric springs, EVs, BESS, and PV (Muthiah-Nakarajan *et al.*, 2021). That study found that 53% of a consumer's residential electricity bill could be saved. These novel studies could be extended by providing a quantitative analysis of the extent of benefits to individual users of optimizing such an energy system. Furthermore, the energy system considered in this study could also be extended to include other elements such as H2G.

The studies mentioned directly above were very relevant in analysing an energy system environment of individual users where EVs could interact with the residential energy demand, and BESS and PV. Given the potential for H2G in the energy system and increasing availability to end users, it would be interesting and important to add the element of H2G into an integrated energy system for individual users for analysis.

To further understand approaches and synergies of EVs integrating in an energy system with BESS and PV, residential energy demand, bidirectional energy flows, and energy management, the literature on the integration for groups of households and microgrids was reviewed. A residential microgrid of up to 10 households analysing economic benefits and grid interaction benefits showed up to 33% cost savings and significantly increased PV self-consumption (Salpakari *et al.*, 2017). The system in this study included PEVs, PV, V2G and space heating load control. Residential BESS was not included. This study had a hypothetical energy transfer agreement between households in the microgrid. The added value of V2G compared to smart charging was found to be limited. This study suggested a separate thermal energy storage could significantly increase heating flexibility. The meaning could be extrapolation and interpreted that additional benefits from a form of energy storage would add flexibility to the system would be a further contribution, such as a BESS. This study only solved for hourly energy balances, which is a coarse time resolution considering the short durations of trips in driving itineraries. The coarse one hour temporal resolution was used in another study (van der Meer *et al.*, 2018). This is an area that could be improved, by analysing at higher time resolution. The electricity bill and peak to average demand of a microgrid of 20 homes were optimized, where the home appliances, PV and PHEV were schedulable devices of each home (Alilou, Tousi and Shayeghi, 2020). In that study, BESS was not included, nor scheduling the charging of the PHEV whilst not at home. Optimal load management of a network of homes connected with EV demand, a public PV park, and BESS, had a focus of optimizing the HEMS element, such as timing of appliances within the

household. (Alyami, 2021). That study considered the EV demand and charging scheduling quite simplistically, with no optimizing of the EV public charging scheduling based on their travel itinerary.

The literature of interest was for single household level integration of EVs with BESS and PV, residential energy demand and bidirectional energy flows, and energy management. To further understand approaches and methodology in the more general integration of EVs with the wider energy system, the literature of such integrations focused on non-residential buildings was additionally reviewed. This additional review was to supplement the additional understanding gained by reviewing the literature of groups of households and microgrids. The literature on synergy of integration for non-residential buildings showed similar studies of synergies which could be cross applied. Similar to studies around residential buildings, there were elements which could be expanded upon. A study on a work place context analysed energy management system using MILP to minimize charging cost, with optimized power flows between the EV, grid and PV (van der Meer *et al.*, 2018). This study also did not have BESS integrated. Optimization and control based energy management for a smart building integrated microgrid with BEV, BESS, PV, wind turbine, micro combined heat and power (Dagdougui, Benchrifia and Ouammi, 2019), showed a good representation of the extent of integration possible, however, was lacking in the extent of focus on BEV interaction and charging need optimization of the BEV. Cost optimization using MILP for a commercial building with thermal and electric storage system, combine cooling, heating, and power system, and PV interconnected with an EV charging station with its own PV panel and B2V, V2B and V2G enabled was an extensively integrated system (Kuang *et al.*, 2017). This study was focused more on EV charging demands, without optimizing the charging demands over the trips. This study did consider the energy interactions for collaborative optimal cost. This study could be compared with a collective energy cost optimization of the BEV and household needs for an individual by drawing parallels with the individual household replacing the commercial building. This study could be extended by considering a more detailed trip data.

There were studies that analysed at a larger scale, such as at nanogrid level. The performance of a nanogrid (University of California, Irvine) connected to PV, EV charging and BESS was assessed (Novoa and Brouwer, 2018), showing 80% renewable contribution to EV charging, and PV penetration of 89%. This study showed the potential benefits of integrating building energy demand, EV charging, PV and BESS. The aim in this study was to minimize drawdown from the grid. The concepts in this study could be extended and adapted to analyses around residential buildings. Furthermore, decision variables for EV charging throughout its trips by approaching more from the angle of the field of transportation could be added. A novel energy management system for buildings connected in a microgrid included EVs as active participants to enable energy transfer from building to vehicle to building with the EV ferrying energy between home and office (Barone *et al.*, 2019). This system included PV and BESS.

Building and mobility energy consumptions were included in the energy balance. However, only the EV commuting energy demands were included, with set times of arrival and departure and travel distance. The concept of the EVs acting as active MES between buildings was very interesting and could have great potential for further study and application. Grid electricity consumption was reduced by up to 77%. This study stressed the need for suitable funding policies to support the development of such microgrids. It would be interesting and significant to extend the concepts in this study by including more comprehensive energy demands of EVs and adding more varied than the used fixed times of arrival and departure. This could be achieved by using a day's travel itinerary data as input.

All of the elements of the energy system discussed thus far were internal within the system. Beyond what could be encompassed in the system, there are external factors could also add further synergy. An external factor affecting the integrated energy system is the concept of real-time, temporally varying, dynamic TOU energy tariffs. These tariffs provide opportunities to use or store energy at opportune times and costs. There are residential energy providers in the UK that have started offering such tariffs. Aiding this, the rollout of smart meters allows the technological requirements. A study analysed with real-time pricing tariff (Alilou, Tousi and Shayeghi, 2020), but used market price of the microgrid, rather than tariff for individuals. Another study that included EVs and temporally varying prices involved analysing an EV charging station with PV, BESS, V2G and hourly energy prices (Domínguez-Navarro *et al.*, 2019). There were economic consequences in regards income generated by the charging station operator. However, the effects of hourly energy prices could not be specifically identified, as the scenario where the hourly energy prices was added also added on other configurations. It would be interesting to study the effects of hourly prices where other variables are controlled for.

The literature reviewed on the integration of EVs, homes, PV and BESS showed some gaps in the literature which could be addressed. A gap identified was analysing all the elements of residential energy demand, BESS, and PV, interacting with BEV charging scheduling for an individual user's full travel needs, with charging decision at each trip as a decision variable. More studies could be found which analysed distribution level, micro or macro grid level that integrated EV demands, PV, and BESS. A comparison of energy management system with and without V2H2G, BESS and PV would an interesting extension. Furthermore, there was another gap in studies based on optimizations of the aforementioned integrated energy system. The gap was that these studies did not discuss a quantitative analysis of the distribution of benefits across demographics.

2.3 Distribution of benefits of EV adoption across demographics

The distribution across society of the potential benefits and costs of EV adoption is an important point of consideration. There are questions over whether the benefits and costs may be concentrated for certain demographics. The literature on the distribution of benefits is reviewed to identify existing and potential issues, as well as attempts thus far at analysing such differential distribution of benefits and costs. The studies reviewed in previous Subsection 2.2 contained no analysis of distribution across society of the potential benefits of the various combinations of BEV, PV and BESS presented.

The analysis of distribution of benefits and costs of the energy system is an important point of consideration. An energy system should distribute the cost and benefits of the energy system equally (Xu and Chen, 2019). From a more sociological perspective, the concept of equal distribution, coined distributive justice, deals with the allocation across society of social goods and ills; these can generally be divided into three aspects (Sovacool, Martiskainen, *et al.*, 2019). The three aspects are: identifying goods and ills that are being distributed (e.g., food, wealth, power); to whom these are distributed (segments of societies, stakeholders, demographics); identifying the most appropriate method of distribution (e.g., based on needs, status, rights). Two of the key questions posed for distributive justice of energy transitions (Williams and Doyon, 2019) are as follows. First, where and how are the costs and benefits of the transition being distributed. Secondly, are the actions reactions to mitigating impacts of events, or proactive planning for future benefits of the transition. The analysis of distribution of benefits of low-carbon transition is important in understanding if some segments of society benefit differently to other segments. Assessing the existence of differential distribution of benefits is important. An example of a study highlighting the importance of such assessments was Monyei *et al.* which found that increasing RES's contribution to the total energy production does not necessarily lead to decreasing residential energy prices, or increased economic equity (2019). Such findings could exacerbate the notion that environmental considerations are for the wealthier portion of the population. For example, in Australia between 2010 and 2017, non-hydro renewable energy grew from 4% to 9% of generation, whilst the average residential electricity price increased by 12% (Monyei *et al.*, 2019).

In recent times, there has been an increase in studies that have considered the social aspects of low-carbon transitions (Sovacool, Martiskainen, *et al.*, 2019). One of the approaches, termed energy justice, involves analysing the justice aspect of such transitions. Energy justice is a concept that refers to the fair distribution of benefits and costs of the energy system; it would be interesting to analyse this quantitatively. Energy justice was defined as “a global energy system that fairly distributes both

the benefits and burdens of energy services” (Sovacool and Dworkin, 2015, p. 436), and “one that contributes to more representative and inclusive energy decision-making” (Sovacool, 2013). Energy justice appraises how energy systems could inadvertently create inequities within society (Jenkins *et al.*, 2016). Sovacool *et al.* noted that most of the discussion in the field of energy justice has overwhelmingly been concerned with ethics and morality among and between humans (2017). Taking that into account suggests that taking a quantitative approach to assessing distributional fairness of benefits and, the issues within energy justice, across society would be an important contribution.

It is important to study the distribution of benefits and costs of low carbon transitions of the energy system, such as BEV adoption and residential PV and BESS. Such studies can aid in determining whether certain demographics within society are affected differently, and if so, to decide whether that requires balancing, and how. Considering both potential benefits and costs are important in providing a full view of the impacts of the transitioning energy system. Martiskainen, Sovacool and Hook noted that previous studies have explored positive user involvement effects of energy transitions, however, that it is important to question the notion, and explore the potential negative effects (2020). A worry is that whilst the low-carbon transition has many positives, it may increase inequalities in society (Newell and Mulvaney, 2013; Henderson, 2020). Risks of not incorporating justice into energy transition were highlighted (Williams and Doyon, 2019). These risks included inequity in availability and affordability of energy during and after the transition. Another risk highlighted was assuming that equal distribution of resources and opportunities will address inequalities in costs and benefits across society. Evensen *et al.* pointed out that there could be uneven financial costs of low-carbon transitions (2018). Indeed, lower income households (LIH) attribute a greater portion of their financial burden towards energy related expenses. In the US, the “affordable burden” of home energy bills was set at 6% of gross household income (Fisher, Sheehan and Colton, 2020). Those who are already financially worse off were hypothesized to be at greater risk of becoming the new fuel poor (Sovacool, Lipson and Chard, 2019). For example, not being able to afford a new BEV could lead to higher cost by having to use less efficient, older ICEVs. Across Denmark, Norway, Sweden, Finland, and Iceland, those with higher income were more likely to purchase an EV (Chen *et al.*, 2020). The findings from that study suggests that the benefits of EV adoption may not be evenly distributed across society. The benefits may be more prevalent amongst those with higher incomes, since that demographic is more likely to purchase an EV in the first place. Similarly, smart home technologies were qualitatively perceived by low income groups to disrupt daily routine, be intrusive, and be non-essential luxuries (Sovacool, Martiskainen and Furszyfer Del Rio, 2021). This evidence would suggest those of low income may be less inclined to adopt smart home technologies.

Sovacool *et al.* pointed out that integrated system analyses of energy transitions are a core gap in the field and represent one of six “new frontiers” for justice research. Xu and Chen raised that there is limited research on the interconnected aspects of smart grid technology adoption, demand flexibility, household activity schedules, and energy affordability, across income groups, and that there is little research that has examined the energy assistance specifically for LIHs, nor the differences across income groups of household energy practices (2019). The broad aspects of distributive injustices of EVs were researched (Sovacool, Martiskainen, *et al.*, 2019), however, the energy justice and distribution of financial costs pertaining to individual operators of BEVs and residential RES and BESS was missing. The effects of low-carbon innovations at the household scale in the UK on energy justice were analysed qualitatively (Sovacool, Lipson and Chard, 2019), without any analysis on the operations of individual’s integrated energy system which may lead to the injustices. This study built on the small amount of existing work on energy justice in an industrialized country. Existing studies have mainly focussed on qualitative analysis for example through interviews and focus groups (Evensen *et al.*, 2018; Monyei *et al.*, 2019; Sovacool, Hook, *et al.*, 2019; Sovacool, Kester, *et al.*, 2019a; Martiskainen, Sovacool and Hook, 2020; Sovacool *et al.*, 2021), rather than quantitative analysis. Quantitative studies on the distribution of benefits of BEV adoption across society were scarce in the literature. Mundaca, Busch and Schwer specifically stated that further quantitative analysis was required to answer distributional questions (2018). That study then elaborated that in methodological terms, the qualitative issues that were identified were insufficient to properly examine how social, environmental, and economic benefits and costs were distributed across society. The need for further empirical research to better understand the contribution to energy injustice of flexibility in household energy demand was pointed out (Calver and Simcock, 2021; Fjellså, Silvast and Skjølsvold, 2021). A study recommended further research involving personality traits and socio-demographics of users, including age, gender, ethnicity, income, that can influence the adoption and use of low-carbon innovations (Martiskainen, Sovacool and Hook, 2020). It seems reasonable to extend recommendation and conclude that further research into the effect of same factors on the benefits for users should also be further researched. Home energy management system including BEV charging, H2G, PV and ESS for a single home to optimize cost (Erdinc, 2014) had no analysis of distribution across sample population or user characteristics. A very relevant study in terms of the integration of the important components, which could be extended by considering the distributional aspects. Milchram *et al.* (2020) aimed to contribute by making energy justice measurable. Their approach was by comparing four implemented smart grid pilot projects in the Netherlands. The projects were given different scores on evaluations. An empirical study explored the different attitudes of different classes of people towards the adoption of smart home technologies (Sovacool, Martiskainen and Furszyfer Del Rio, 2021). Some

links between smart homes and energy consumption, and possible negative impacts to poverty, inclusion, and empowerment were found. For example, the study found that there were disempowering attitudes for the poor or those who are not technology savvy. These studies were good examples of adding to the literature analyses that were more quantitative. A further step forward would be to analyse quantified costs and benefits of the changing energy system, and the distribution of the costs and benefits.

The current energy system was shown to have differential distribution of benefits and costs across society. Therefore, a quantitative study of the distribution of the benefits of low carbon transition adoption could be significant. Such a quantitative study could show to what extent the potential inequity of distribution of the benefits and costs of low carbon transition adoption could be. An inequity in the distribution of the benefits of low carbon transition adoption could be attributed to many reasons, such as the financial burden of acquiring a BEV or other low carbon technologies. Upgrades to improve energy related costs often have high upfront costs, and these can seem daunting for LIHs (Drehobl, A., Castro-Alvarez, 2017). This lack of accessibility can lead to greater energy costs for those who do not, or cannot, access such upgrades. In the US, LIHs spent \$1.23 per square foot on utilities compared to \$0.98 for all other households according to the American Housing Survey conducted by the U.S. Census Bureau (Drehobl, A., Ross, 2016). Energy efficient household appliances which can contribute to reducing energy bills were more prevalent in households with increases in income, especially for homeowners compared to renters (Xu and Chen, 2019). Without intervention, cost saving technologies such as BEV, BESS, and PV may also be more prevalent in households with higher income, leading to further disparity of proportionate expense on energy across income levels. Similarly, smart meter prevalence was found to increase with income, with 18.0% for LIHs, to 23.2% to middle-income households (MIHs), to 26.8% for high-income households (HIHs) according to Residential Energy Consumption Survey in the US (Xu and Chen, 2019). The benefits of existing residential PVs in the UK were not evenly distributed, and favoured those with higher incomes (Sovacool, Lipson and Chard, 2019). In Germany, users who benefited the most were those with the financial and physical capability to install PV early and benefit from Feed-in-tariff (FIT) (Martiskainen, Sovacool and Hook, 2020). There is evidence to suggest that similar disparity could occur for adoption of BEVs. Regarding general motoring costs, not specific to EVs, those in lower income areas in the UK were found to spend a larger proportion of their income on motoring costs (Chatterton *et al.*, 2018). Therefore, it is possible that those with lower income may incur disproportionately higher costs of BEV operations. There were distributive injustices found through expert interviews, focus groups and internet forums (Sovacool, Kester, *et al.*, 2019a; Sovacool, Martiskainen, *et al.*, 2019). EV ownership in Norway was limited to those with higher income (Sovacool, Kester, *et al.*, 2019a; Sovacool,

Martiskainen, *et al.*, 2019), and increased congestion for busses (Sovacool, Kester, *et al.*, 2019b). In Great Britain, energy bills were higher, even for non-adopters of smart meters (Sovacool, Kester, *et al.*, 2019b), which would lead to LIHs spending a disproportionately larger proportion of their income.

The literature has suggested some ways of balancing the distribution of benefits and costs of low carbon transition. Generally speaking, the recommendations and policies suggested were not specific or actionable but took the approach of suggesting the overall aims of the policies. Considerable work was deemed to be required if policymakers want to ensure smart home technology adoption does not increase vulnerability, deskilling, and exclusion (Sovacool, Martiskainen and Furszyfer Del Rio, 2021). Considering the energy transition as an opportunity of system transformation was proposed (Williams and Doyon, 2019) as a mitigating strategy to overcome the risks of distributive injustice, however, no more specificities were outlined. The discussion of what “policy” should do for benefits was lightly covered, without proposing specific policies (Noel, 2017). Sovacool, Hook *et al.* gave policy recommendations on balancing spatially distributed energy injustices focussed on the whole system (2019). These included benefit sharing agreements across the supply chain of various energy system components, and accounting for externalities such as toxic pollution. However, there were no recommendations which would allow direct actionable steps for or by individual users on improving the energy injustice affecting them, or on information pertaining to it. Policy recommendations on balancing system level energy injustices due to the far reaching effects of the interconnected energy system were proposed (Sovacool *et al.*, 2021). The imbalances discussed included the effects on miners in Africa of raw materials required for EVs to be used in Europe. An interesting area of recommendation was the promotion of new business models, such as mobility as a service. However, the study stopped short of providing recommendations that can lead to direct actions for or by end users. The need for energy policy to not only focus on the needs of today’s poor, but also tomorrow’s is important (Sovacool, Lipson and Chard, 2019). However, there were no concrete suggestions on the potential to link policy to consider EVs and PVs together, with differential distribution of benefits and costs in mind. Policies that take into account distributive aspects were recommended, such that some users do not benefit at the expense of others (Martiskainen, Sovacool and Hook, 2020). However, no clear pathways on how to achieve these were outlined. Policies play a key role in adoption of PEVs and there is a need to focus on policies that provide longer term effects (sales of EVs) and evaluation criteria of policies beyond effectiveness and cost to include others such as simplicity (Melton, Aksen and Moawad, 2020). A quantitative study analysing the economic viability of EV and PV system for residential households in Japan recommended that policy supports to provide remuneration for excess electricity from PV was important in achieving increase of PV self-sufficiency and decreasing CO₂ emissions (Kobashi and Yarime, 2019). Governance principles were suggested to avoid

distributive injustice of costs and benefits of smart grids (Milchram *et al.*, 2020). The suggested principles included monitoring of individual's behaviours; sanctions for users who violate collective rules; recognition of the community-governance by external governmental authorities. The existence of principles to deter unfair partaking of smart grids would be important in establishing an equitable distribution of the changes of the energy system. It would also be important to have guidance for principles which encourage fair participation. There were suggestions for policies to aid in the wider adoptions of BEV, BESS, PV, and integration with the grid, but without any consideration of the distribution across society of the associated benefits and costs (Thompson and Perez, 2020).

A quantitative study of the distribution of benefits and costs of low carbon transitions including adoptions of BEV and residential PV and BESS could benefit society by enabling a fair distribution and is currently a gap in the literature. For example, a fair distribution would allow LIHs to spend more on other aspects of life that can help development, such as education. An overall more efficient energy system could lead to more sustainability, both through DER as well as greater utilisation of RES in the wider energy system. There was little research that gave recommendations on balancing distribution of benefits and costs of the changing energy system based on the most suitable technology setup for individual users, nor what policies could aid in encouraging the individuals as such.

2.4 Summary

The literature review presented a selection of the relevant works in areas related to this thesis. This involved reviewing studies that integrated different components of EV charging, V2H2G, building energy demand, PV, and BESS. Specifically, studies related to individual EV operations and individual residential homes were sought. The reason those studies were sought was because it was deemed that considering the changing needs of an EV throughout its full travel itinerary was important. Segregating out the optimization for one of public or home charging would defer the inevitable cost to the user out of the scope of study. The perspective of an individual EV user is important given the amount of information that needs to be processed by users in making charging scheduling decisions. Studies relating to the distribution of benefits and costs of the changes in the energy system was then reviewed. The relevant changes were ones which impacted the integrated energy system as mentioned previously. The review of the distribution of the benefits was important to determine the state of the art of the potential differential distribution of benefits of low carbon transitions including BEV adoption and residential PV and BESS. The areas of literature reviewed pulled together how these

low carbon transitions could interact, the potential benefits, and how those benefits may be distributed across society.

Based on the analysis of the papers reviewed above, to the author's knowledge, there is a gap in the literature of quantitative analysis of the differential distribution across demographics of benefits of optimized BEV energy management in an integrated system. The integrated system involves an individual's residential, BESS, PV and V2H2G. The system ensures meeting the individual's full travel needs and residential energy demand using real travel data. Furthermore, presenting as a tool supporting charging decisions for users by optimizing the charging and discharging instances of the BEV whilst in public and at home, together with optimizing the energy management of the BESS, and instances of V2H2G under one system was not seen in the literature. There was a lack of a single framework which integrates such a system, which would allow a quantitative analysis.

The gaps analysed formed the basis of the research questions to be answered by the research in the thesis. The answering of the questions was enabled by the formulation of the framework and optimization, the solving of it, and the analysis thereafter. The research questions (RQ) being answered are:

- RQ1: What are the extents of financial benefits to individual BEV users of having a DST that processes the large amount of information in charging choices? The DST would optimize the total BEV needs in public and home from an individual's perspective in one analysis, as opposed to separating them out for building centric, or BEV centric approaches using real travel data to specifically detail each trip characteristics to calculate trip energy demands, and the associated locational charging rates.
 - How are the benefits affected by the travel pattern characteristics of the BEV users?
- RQ2: What are the extents of financial benefits of harnessing synergy of integrating BEVs, V2H2G, residential PV and BESS to interact with each other, and optimize energy management to minimize electricity cost of the user's energy environment?
 - What is the comparison of benefits to BEV users of a segregated system, to an integrated one? What are the effects on the extent of financial benefits of H2V, V2H and H2G?
 - What are the effects of BESS and PV capacities on the extent of financial benefits?
 - Do the travel pattern characteristics of BEV users have an effect?
 - What important insights can be synthesised regarding the integration of the energy system and system parameters to inform policy makers and businesses involved in supplying relevant products or services?

- RQ3: How are the benefits distributed across demographics (income, ethnicity, employment status) of the BEV users? Is there inequity in distribution?

More specific questions and further hypotheses based on these research questions are detailed in Subsection 3.4.1.

Chapter 3

Methodology for analysis of extent and distribution of financial benefits for individual BEV users

The literature review in the previous chapter highlighted a gap in the literature of quantitative analysis of distribution of benefits of low-carbon transition in understanding differential benefits across segments in society. The limitations of the current conceptual frameworks for an integrated system were also found. What was lacking was one framework which integrates into one analysis the BEV charging scheduling, V2H2G, residential energy demand, BESS, and PV, from the perspective of an individual user, using detailed full day travel data.

The research in this thesis proposes an analytical framework to quantitatively analyse the extent and distribution across society of the financial benefits for individual BEV users of optimization of energy management of an integrated energy system comprising of BEV, residential energy demand, BESS, PV, and V2H2G. This study proposes a conceptual framework to capture the proposed integrated energy system. An optimization problem was formulated that minimizes the electricity cost of an individual BEV user's integrated energy system captured by the conceptual framework. The optimization is achieved by optimizing the energy management within the system with decision variables capturing the energy management of the system. The results were analysed using regression to yield insights. These steps enable achieving the objectives of the research (detailed in Section 1.2) and addressing gaps in the literature (detailed in Chapter 2).

The frameworks are presented in this chapter in Sections 3.1 and 3.2. Section 3.3 outlines the potential financial benefits from optimization and the calculation methodology. Section 3.4 summarises the chapter. The solving of the optimization of the integrated energy system is discussed in the next chapter. This chapter contributes to accomplishing RO1.

3.1 Analytical framework for quantitative analysis of the distribution of financial benefits across demographics, effects of travel pattern characteristics and effects of the components of the energy system

The analytical framework enabled answering the research questions and addressing the gap in the literature of a quantitative analysis of the distribution across demographics of financial benefits of optimized BEV-home energy management. By conducting a quantitative analysis with the analytical framework, these can be better understood:

- How the financial benefits are distributed across the different demographics across society.
- Which segments might benefit more?
- How travel pattern characteristics and energy system parameters affect the extent of financial benefits.

The analytical framework (Figure 3.1) contains the steps taken from input data, optimization of the integrated energy system represented by the conceptual framework, followed by the regression analysis of the results.

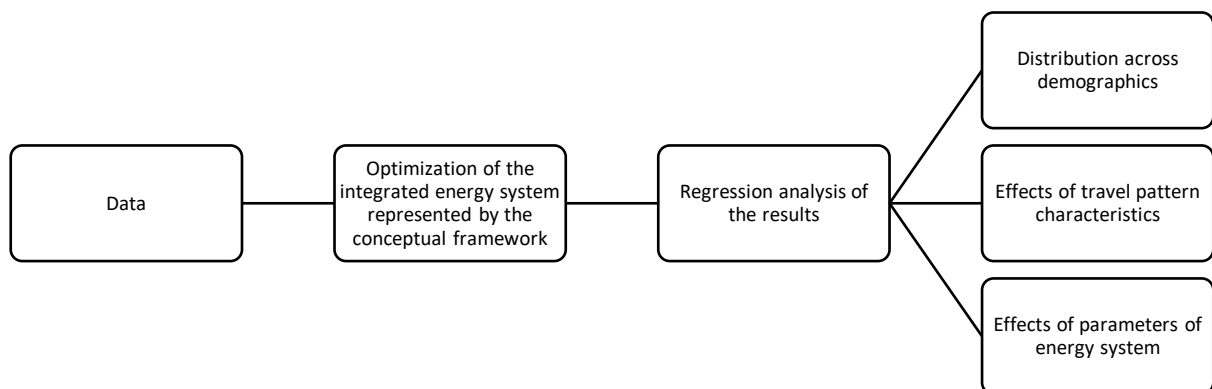


Figure 3.1 Analytical framework

3.2 Conceptual framework for the proposed energy system of an individual BEV user integrating energy interactions between the BEV, residential energy demand, BESS, PV, and V2H2G

This thesis presents the conceptual framework representing the author's view of the energy interactions possible between the components in an integrated energy system for an individual BEV user. The components of the system are the BEV, residential energy demand, BESS, PV and interactions between these and the grid via V2H2G. The BEV acting as a MES facilitates a spatiotemporal interaction between the public grid and the home, fixed around the individual's mobility needs. An energy management system optimizing the interactions represented by the conceptual framework could lead to financial benefits for the user by minimizing the users' electricity cost. The conceptual framework allowed researching the extent of financial benefits in optimizing the energy management of the integrated energy system, and the synergy that exists between its different components. The effects of the parameters of the components on the financial benefits were also studied by varying the parameters, such as storage capacity of the BESS. Optimizing the system represented by the conceptual framework allowed analysing and presenting a quantitative analysis of the distribution of the benefits.

The conceptual framework represented the energy system of an individual BEV user. The framework captured the total electricity costs (both home and public charging) associated with the BEV mobility energy demands. The perspective of an individual user for the conceptual framework was used as the literature showed a gap of an individual focused study using such an integrated energy system as outlined thus far, using real, trip-level detailed travel data, and quantitatively analysing the distribution of financial benefits for individuals across demographics. Furthermore, taking this perspective allowed addressing the research question of the effects of the configuration of the energy system of an individual BEV user on their financial benefits, rather than analysing the effects of widespread adoption of certain technologies across a sample population.

In the following subsection, the conceptual framework is presented, followed by a discussion on the components included in the framework. In the subsequent subsection, the approach of taking the perspective of an individual BEV user for the conceptual framework is further discussed.

3.2.1 The Conceptual framework

The conceptual framework developed in this research captured the interactions of the different components in the integrated energy system of an individual BEV user, fixed around the mobility needs of the individual, and from the perspective of the individual. The conceptual framework captured the integrated energy system consisting of the BEV, residential energy demand, BESS, PV, and interactions with the grid via V2H2G. In reality, there are multiple pathways of energy transfer

that can take place between the different components with many being bidirectional (Figure 3.2); this is quite a complicated system.

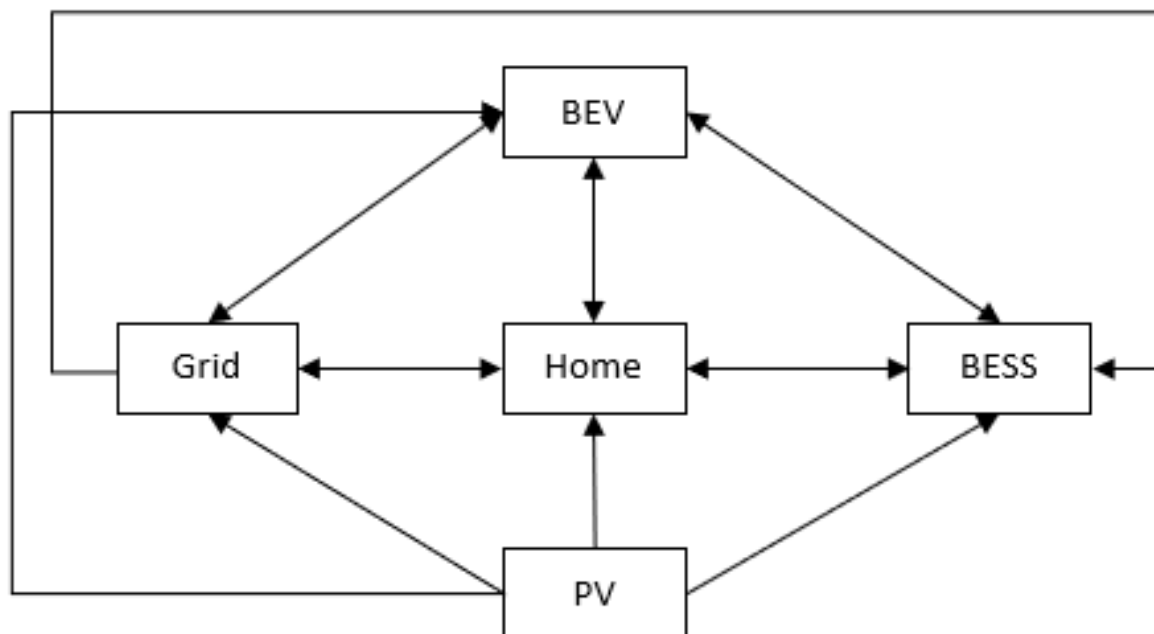


Figure 3.2 Possible energy flows between the components of the integrated energy system.

The conceptual framework captured these connections in an organised and simplified manner and can be seen on Figure 3.3. In the conceptual framework representing the integrated energy system, the home acts as the central connection point for the household energy environment. The home also acts as the gateway connection point between the BEV and the home environment. As seen in the figure, the home acts as the connection hub of the residential energy flows, with the bidirectional energy transfer from the grid to the home, and the home to grid (H2G), and the flow to and from the BESS, and the PV energy flowing to the home. The home acts as the connection point for the BEV to interact with this home environment.

Whether the BEV can interact with this home environment or not is dependent on whether the homeowner can connect the BEV to the residential energy circuit, via a home charger. Therefore, the type of connection will depend on whether the homeowner has access to private off-street parking that would enable the installation of a home charger. If the homeowner does not have access to a home charger, they would not be able to connect to the user's home energy system. If this is the case, the BEV would be using an on-street charging point, even when parked at home.

The PV can supplement the residential energy usage, charge the BESS or the BEV, or export to the grid (H2G). The BEV interacts with the grid when it is in public, and also whilst at home through the home (V2H2G). The dotted box shows the energy balance (demands, generation, and flows) that this conceptual framework optimizes. The balance sums the net energy purchased and sold to the grid.

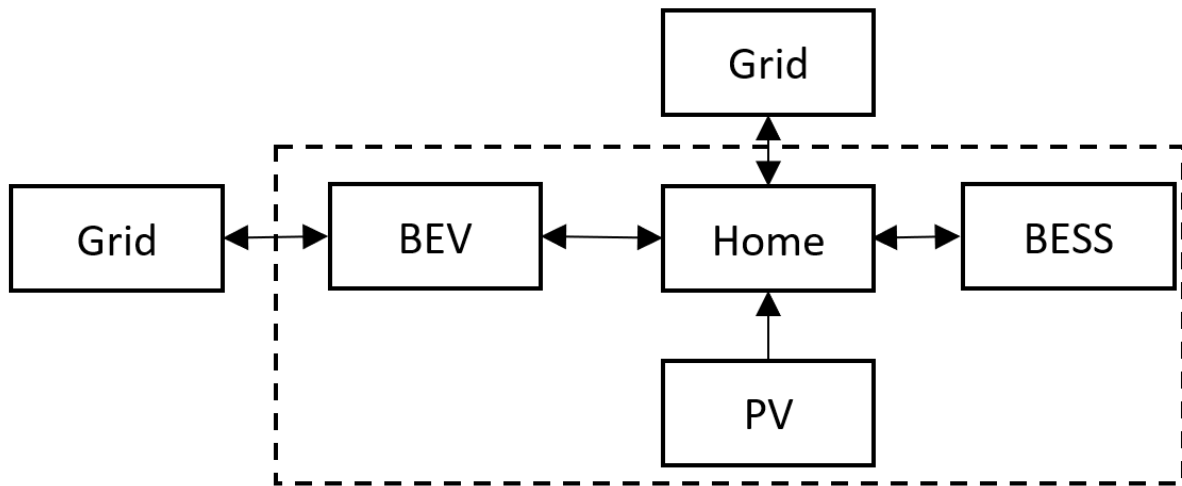


Figure 3.3 Conceptual framework representing the streamlined set of all possible flows of energy between the components. The energy flows to be optimised are enclosed within the dotted lines.

The capturing of this integrated energy system within a single conceptual framework allowed the investigation of the extent of benefits to individual BEV users of optimizing their charging scheduling within the context of an integrated energy system environment, based on their mobility needs. Then the insights on the distribution of these benefits in a wider context could be analysed. How the extents of benefits are affected by the user characteristics, and the insights of the accumulated benefits to society were of interest.

The conceptual framework sought to capture the different technologies that an individual BEV user could access, namely BEVs, residential BESS, PV and V2H2G (

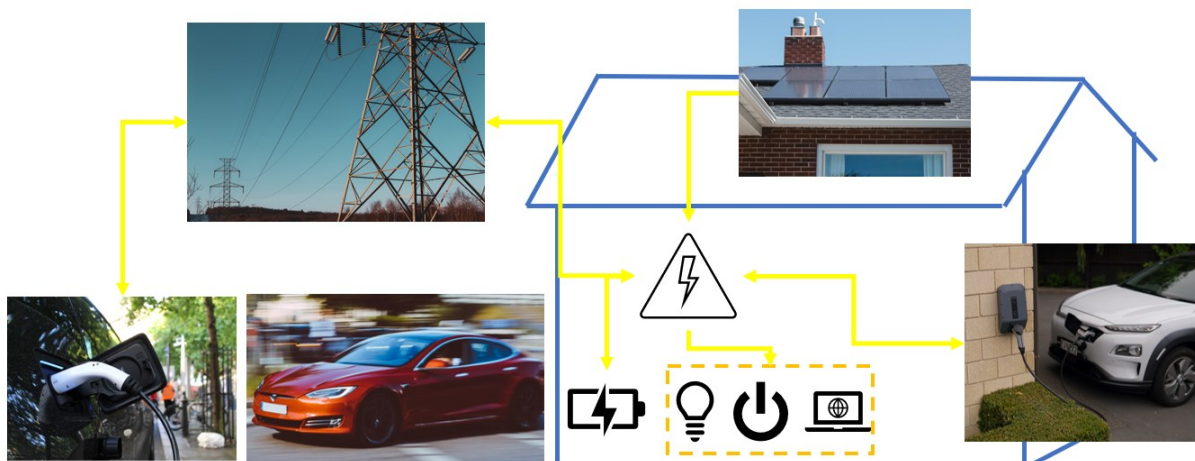


Figure 3.4). Researching the interactions between these technologies which form the components of the integrated energy system was deemed important given the increasing adoption of them within society. Capturing these in the conceptual framework allowed investigation of the interactions and synergies within this system, between the components. Figure 3.5 shows the schematic of the integrated energy system captured by the conceptual framework.

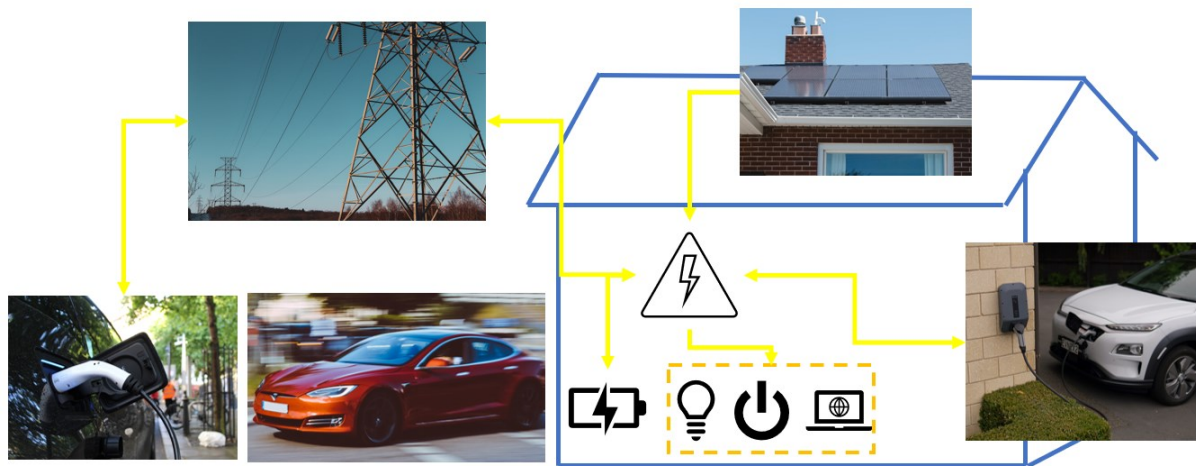


Figure 3.4 Components of an integrated energy system accessible to an individual BEV user.

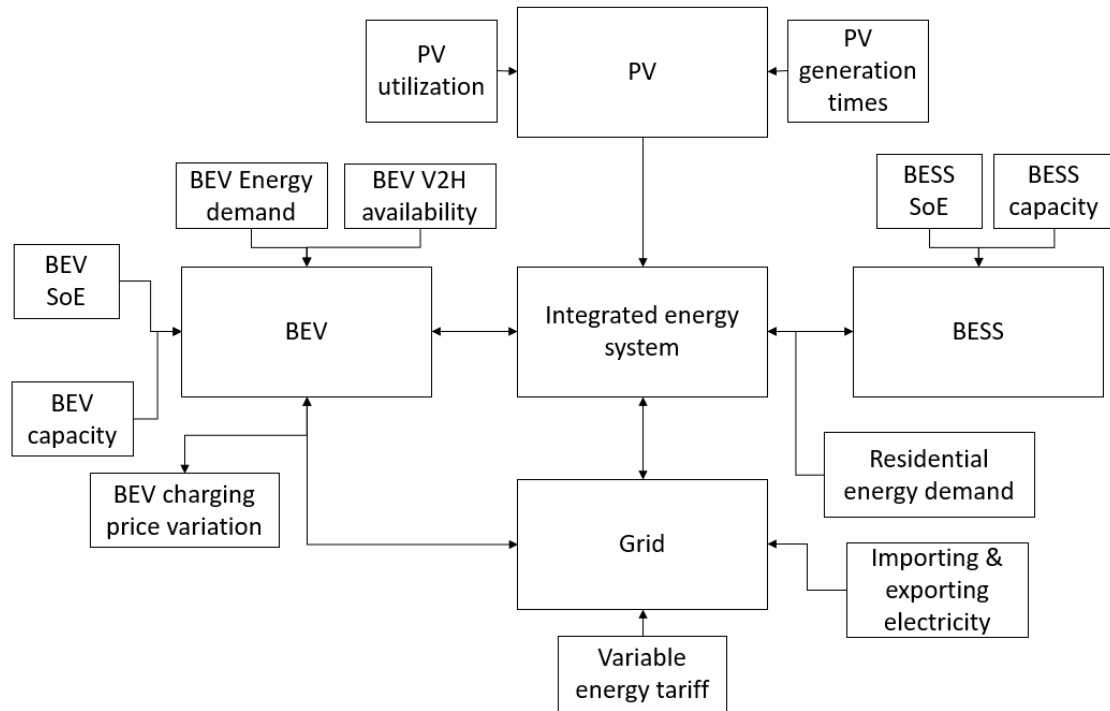


Figure 3.5 Schematic of the integrated energy system captured by the conceptual framework.

Figure 3.6 shows the net electricity flow of the BEV user within this conceptual framework. This representation has streamlined the inputs and outputs of electricity between the individual and the grid.

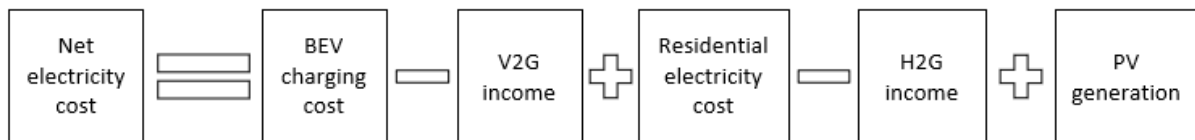


Figure 3.6 Net energy use for the BEV user

3.2.2 Perspective of an individual BEV user for the conceptual framework

The conceptual framework representing the integrated energy system was from the perspective of an individual BEV user and their home.

The literature review highlighted the need for a study with an approach taking the perspective focusing on the individual and taking into account their full mobility and charging needs, in conjunction with their residential energy needs. Existing approaches were short-sighted by including within scope of analysis only a subset of the full charging needs. The literature review highlighted the commonly

taken EV centric approach based on the movements of the EV which sought to optimize the charging scheduling in public only. An alternative approach revealed by the literature review took a building centric, or home centric approach, to which EVs travel, and EV charging was thus optimized in conjunction with the energy uses, storage and generation of a building. In the building centric and home centric approach, the charging of the EV in public was not optimized. Both of these approaches lack in considering the full needs of the EV's energy demands by optimizing for the full charging scheduling; optimizing only for the public, or at building charging displaces the rest of the energy optimization out of scope. This approach could lead to deferring the demand and cost out of scope. This would result in a non-optimal cost of operation for the user, who in reality must pay for the deferred cost. That is, if only the cost of the charging in public is optimized for, and the charging at home is out of scope, the cost of charging once at home is not considered part of the cost, but in reality, the user would be paying for it through the residential energy bill. For example, in an EV centric approach optimizing only the EV's public charging, and the EV returning home with an assumed or non-optimized SoE, the charging necessary to meet further mobility needs was not optimized for, and it may have been cheaper to pre-charge for those needs in public. Similarly, for building centric approaches, where the public charging scheduling for the EV was not optimized and could lead to needing to charge at non-optimal prices in public.

This research adopted the individual centric approach where the full travel itinerary charging schedule of the BEV was included, along with the user's residential energy needs. This approach represented the individual user's full travel needs and charging demands and costs within the conceptual framework. This inclusion allowed analysis of the total electricity cost to a BEV owner under one framework. It was important to include the residential energy costs within the conceptual framework, as any charging the user must do at home contributes to the residential electricity cost and will be incurred by the user. Not including it would have led to displacing the charging to residential energy cost, which in reality the user would still have to pay for. This approach sought to include within the conceptual framework the synergy in integrating the energy system environment of an individual BEV user by including the potentially flows of energy between the components in the optimization of the energy management.

The conceptual framework representing the perspective of an individual BEV user had to include the points of consideration and needs of the user. These were collated to ensure the conceptual framework would incorporate these dimensions (outlined in Figure 3.7). The many needs and variations make the system complex for BEV users. This then makes the decision making more complicated and difficult for the users as they seek to find a balance between ease of operation and lowering charging cost of the BEVs. The less the users plan ahead, the easier it would be for them, but

the more it may cost them. If the conceptual framework could capture these difficulties posed by BEV operations, the optimization based on the conceptual framework could optimize and condense the decision making for the users and yield an optimal charging scheduling and energy management.

The scope was focussed on individual, privately operated vehicles. Fleets were not considered. The conceptual framework was formed accordingly. The importance of fleets in urban areas is not dismissed. The impacts on insights of the research of the exclusion of fleets from scope is that a large number of BEVs being operated in urban areas are not being analysed for. However, to enable completion of the analysis with given resources and to fulfil the main aims of the research, this researched was focussed on privately operated vehicles. Furthermore, given the LTDS was the primary source of travel data (further explained in subsection 5.1.1), fleet operating travel data was not available. However, this framework could be applied to analyse for fleets to give results at a high-level. The analysis could be undertaken by having an individual BEV's travel data represented that of one fleet, or subset of a fleet, thus giving the charging demands. This would involve changing the input data of an individual with the travel demands of a fleet by aggregating the demands at each time period across the fleet into one travel itinerary.

The scope in terms of household focussed on one household. This household was characterised by the number of residents in the household. There was no characterisation for type of tenant, such as owner, rented, council etc., nor was there characterisation for multi-family households. The framework could be used to analyse these further characteristics by having additional input variables. This would require appropriate input data. The additional data could be used as additional variables in the regression analyses to analyse the effects these variables have on the results.

As the scope was focussed on one household, commercial buildings or facilities were not part of the scope. The focus to align with the research aims of analysing equity of distribution of benefits to individual users. Furthermore, there were more studies which focussed on commercial buildings or facilities found in the literature, than there were studies focussing on individuals. Thus it was deemed greater gap in the literature was on the subject of individual households. This framework could be readily adapted to commercial buildings by using commercial building energy demand data as the input. Commercial building data could be used in lieu of household energy data. BEV charging demands could be adapted either by aggregating multiple BEV charging profiles into one, and using that data in place of the individual BEV charging demand. Another method is by adding multiple BEVs as charging demands and MES into the framework.

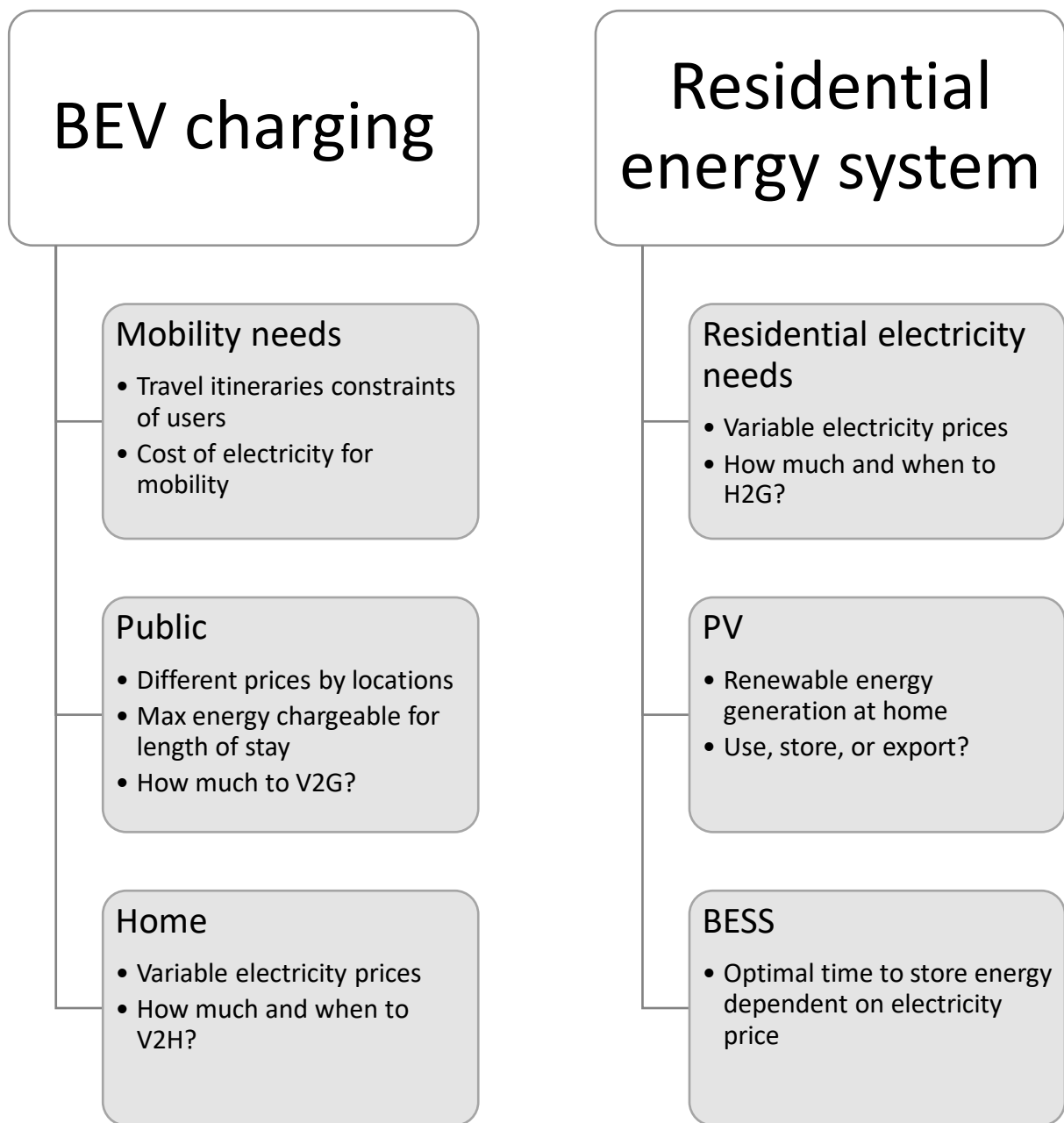


Figure 3.7 The needs and considerations of a BEV user and how they fit into their energy system environment.

3.2.3 Definitions of electricity flows

The specific definitions of the different electricity flows in this research are outlined in this subsection. Figure 3.8 shows the different flows of electricity and the relation to the framework.

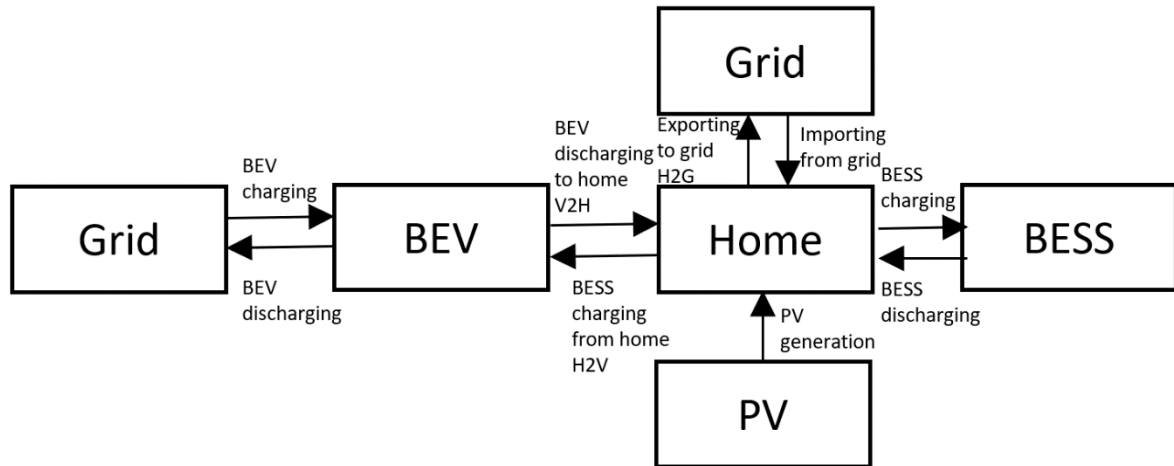


Figure 3.8 The flows of flows of electricity possible in this framework.

3.2.3.1 Charging

The charging of BEV refers to the electricity flow to the BEV. When in public, this is directly from the grid. At home, this can be either directly from the grid, or from the grid, BESS, or PV via the home.

3.2.3.2 Discharging

The discharging of BEV refers to the electricity flow directly from the BEV to the grid when in public. At home, the BEV could be discharging to the grid, or via the home to the BESS or grid.

3.2.3.3 V2G

V2G is the discharging of the BEV to the grid when in public to gain an income.

3.2.3.4 V2H

V2H is the discharging of the BEV to the home, which can be for the purpose of storing in the BESS for later use, or to supplement residential electricity demand at that time, or sell to the grid via H2G.

3.2.3.5 H2V

Home-to-vehicle (H2V) is the charging of the BEV via the connection between the BEV and the house. The electricity could be from the BESS or PV, or from the home-grid connection, in which case it will be at price of the residential energy plan.

3.2.3.6 H2G

This is the selling of the energy to the grid from the home. The source of the electricity can be from the BEV, the BESS, or PV.

3.2.3.7 *Importing from the grid*

This is the flow of electricity from the grid to the home. The purpose of this can be to meet the residential electricity demand, to store the BESS, or to charge the BEV.

3.2.3.8 *Residential energy demand*

This is the fixed residential energy demand of the household.

3.2.3.9 *PV*

This is the electricity generated from the PV. It first flows to the home, at which point it could be stored in the BESS, sold to the grid, meet the residential electricity demand, or charge the BEV.

3.3 Calculations and analysis of financial benefits

Financial benefits for individual BEV users can be obtained by optimizing for cost the energy management of the system captured by the conceptual framework with the perspective of an individual user. By optimizing for cost, the overall cost of importing and exporting to and from the grid will be sought to be minimized. The decision variables at each point in time will be not only how much to charge the BEV, but how much to store in BESS, import/export to grid, and by proxy, how much of the energy demand should be met via grid, or PV, or stored energy. Because the conceptual framework captured the intermediary interactions between the different components of the system, synergies that exist between them can be harnessed within this optimization. The synergies include harnessing opportune energy prices to store energy at cheap times, storage of excess PV generation with anticipation of usage later when energy prices are higher, and the usage of the BEV as a MES that can move energy spatially to take energy from cheaper locations to more expensive, and to move energy temporally to store energy for more expensive times.

3.3.1 Regression analysis

The results of the optimization were analysed with regression analysis to achieve the objectives of the research (detailed in Section 1.2) and address gaps in the literature (detailed in Chapter 2). The analysis methodology is discussed in further detail in Section 6.1, along with presentation of the results for better clarity and to present together the relation between the methodology, what is being analysed, and to aid understanding of the results and insights presented.

3.4 Summary

The purpose in formulating the analytical framework is to assess the extent and distribution of benefits of optimized BEV operations in an integrated energy system, and effects on the benefits of the interactions of the BEV with the energy system. The motivation is to yield insights which can inform the various stakeholders, including individual users, governments and policy makers, and businesses such as BEV manufacturers and dealers, charging service providers, and residential energy providers. The insights can inform these entities to aid in a more sustainable future.

The framework enables achieving the objectives of the research by combining the different aspects of the energy system around BEV adoption for individual users. The solving of the optimization problem enables the analysis of the extent of benefits to BEV users of a DST condensing the amount of information they have to process regarding the differences in charging options and the amounts to charge at each location, based around their mobility needs, where each trip and stay in the full day travel itinerary is used, and charging at each of those locations are decision variables to be optimized. The framework allows the analysis of the extent of benefits of BEV integration with the energy system involving charging and discharging at home via the residential grid connection (H2G), with the potential synergy and benefits of BEVs acting as MES to transport energy spatiotemporally. This enables the analysis of the potential of harnessing the synergy of energy flows between BEV and the grid, and the associated costs and incomes. Further intricacy to the system is added through half-hourly energy pricing for both importing and exporting at home. Sensitivity of results to pricing is gauged through analysing different pricing scenarios. The framework enables the analysis of the extent of benefits to BEV users of integrating their energy system to further include BESS and PV at home and BEV users of integrating their energy system to include BEV charging discharging (V2G) in public. This allows answering the research question of the benefits analysable from integrating the different components of an individual's energy system such that the components can interact with each other through energy flows.

The structure in which the testing simulations were formulated enabled analysing the extent of financial benefits for individuals, depending on their technology configuration of BESS, PV, and others. The approach taken was to assess the potential impact of choices of configurations for individuals, rather than analysing based on assumed widespread segmented adoption rates of different technologies across the population.

3.4.1 Research hypotheses and policy questions

The conceptual and analytical frameworks presented in this chapter enables shaping the hypotheses and policy relevant questions that can address the research questions stated in Section 2.4. Therefore, the key contribution of this chapter is to present a structured framework to analyse future RES with complex configurations from the consumer perspective.

Whether thinking ahead for more than a day would affect the extent of benefits, and if so, how much, is also of interest. Therefore, multiple day time horizon optimizations were also modelled, and the results compared and analysed. This answers the hypothesis of the longer time horizons yielding greater benefits. This is achieved by analysing the impact of time horizon on the benefits.

Through the solving of the optimization, a contribution can be made in analysing the distribution of the benefits to BEV users of such an integrated system. Analysing how the distribution is related to BEV characteristics can yield insights to the equity of the distribution. It can also yield insights to the worth of investing in different technologies, based on the user characteristics through associating the characteristics of BEV users with the most beneficial technologies. This will allow pinpointing the technologies that will be most worth acquiring for each BEV user. Comparison of benefits for those with access to charging at home, and those without can be analysed. The results of this will give insight to whether home charging infrastructure adoption should be encouraged, and the extent of benefits based on different characteristics of BEV users, and thus for whom it should be prioritised, and more encouraged.

A further contribution is in analysing the impacts to society of individuals optimizing for their own costs, through analysing the aggregate energy flows, such as H2G provision. Further, the research can provide insights for policy makers and businesses in determining the pricing that is most beneficial to them, through analysis of the effects of pricing on the aggregate energy flows or benefits to users. This formulation can also yield insights for the grid operators, as lower energy prices may be a proxy for times of lower energy demand, or surplus production; the latter could also be at times of surplus renewable energy production. Thus, changes in charging times due to temporal charging costs, and how much grid services could be available for grid operators, and different yields depending on price signals, could be analysed.

Further contributions include yielding insights from, and being able to, the analysis of the aggregated optimized impacts of integrating an energy system for BEV users, such as RES utilisation, and V2H2G provision. How the adjusting of pricing of energy import, export and charging by policy makers and

businesses can yield different results and practising of targeting of different profiles of BEV users for desired outcomes can also be analysed.

What the extents of financial benefits to individual BEV users of having a DST that processes the large amount of information in charging choices can be answered. This is achieved by analysing the results of the optimization and comparing to the baseline scenario. Further, this enables analysing the distribution of the benefits and how the benefits correlate to the characteristics of BEV users.

Specific questions and hypotheses tested based on the research questions in Section 2.4 are:

- Hyp1: The DST will lower operating cost through optimising the charging decisions. Thus, users will benefit by being aided in their decision making.
- Hyp2: There will be a positive relationship between extent of financial benefits and BEV user driving mileage and number of stays.
- Hyp3: Longer optimization time horizons will increase the percentage of benefit gained. That is, a time horizon that is twice as long, will have greater than twice the total benefit, and a higher per day benefit.
- Hyp4: There will be little effect on the extent of financial benefits of differences in BEV characteristics where the overall mileage of the BEVs stay similar (Nissan Leaf, Hyundai IONIQ, MG ZS).
- Hyp5: The higher specification BEV (Tesla Model Y) will yield greater benefits than the others. The increase in benefit can be compared to the increase in BEV purchase cost to compare whether it is financially better in the long term to invest in a more expensive, higher specification BEV.
- Hyp6: Each of the individual components (access to charging at home through H2V, V2H, H2G) will lead to extra financial benefits for the users beyond those gained by the optimization of charging scheduling only (as in Formulation 1).
- Hyp7: Individuals optimising for their own operating costs can benefit the energy system through provision of grid services (H2G).
- Hyp8: Access to real-time dynamic TOU residential energy tariffs will yield greater benefits as the DST has more opportunities to harness the opportune prices. However, without BESS, the benefits will be less pronounced, as the only access to store the opportune energy prices is through the BEV.
- Hyp9: PV and BESS will individually give operational cost benefits to users.

- Hyp10: Individuals optimising for their own operating costs can still have benefits to the system through utilisation of PV (RES), and therefore less stress on the grid, services to the grid through H2G, V2G, and lower grid emissions.

Policy questions (PQ) which can be answered by this framework are:

- PQ1: Should BEV users be encouraged to optimize their charging scheduling to save financially?
- PQ2: What are the extents of benefits of all BEV users being having a home charger installed to charge connected to the home energy plan? Should home charging infrastructure instalments be encouraged?
- PQ3: What are the financial benefits to a BEV user of coupling a PV and/or BESS to a home that charges BEVs, with optimized charging scheduling based on the full day travel itinerary detailing each trip? How are the benefits affected by the size of PV and BESS? How do the benefits compare to the cost of installing the technologies?
 - What are the effects to cost savings for people, V2H2G provision, RES utilisation, and drawdown from the grid of different PV and BESS sizes?
- PQ4: How are the benefits distributed based on BEV user driver characteristics such as mileage, and number of trips?
- PQ5: How are the benefits distributed based on BEV user social characteristics such as income, and neighbourhood of residence in London?

This chapter presented the analytical framework of the research, outlining the steps from usage of the data, solving of the optimization of the integrated energy system captured by the conceptual framework, and the regression analysis performed. The conceptual framework presented by this research was discussed, which represented the integrated energy system for an individual BEV user, consisting of the different technologies they would have access to, with the conceptual framework being applied from the perspective of an individual user.

The following chapter details the optimization problem being solved within this research.

Chapter 4

Problem formulation for optimized charging scheduling and energy management of individual BEV drivers integrated with V2H2G, residential energy demand, residential battery storage, and residential solar generation

The framework in the previous chapter captured the way the different components of BEV adoption and residential energy system could be integrated. This chapter introduces problem formulations that optimize the energy interactions of a BEV user with the integrated energy system described in the previous chapter. First, the chapter formulates the general optimization problem representing all the interactions of the driver with all system components. Then the problem is specified in three specific formulations for which the problem is solved in this study. The specifics of the model such as the data used, and parameters chosen are detailed in the following chapter.

There are three formulations of the optimization configuration, each adding elements of the holistic integrated energy system framework. Each formulation has multiple scenarios where scenario parameters are varied to test for effects of different components of the system. This enables answering research and policy questions relating to each element of the system and detailed in Section 2.4. The research questions each formulation answers receptively are outlined within the

subsections for each formulation in Section 4.2. The different scenarios enable obtaining results of the extent of benefits with other variables controlled for. Formulation 1 captures the optimized charging scheduling for BEV users, variations in BEV specifications, and number of days of optimization time horizon. Formulation 2 adds interactions of the BEV with the residential energy system through V2H and H2V, residential energy demand, and different pricing scenarios including real-time dynamic TOU tariffs. Formulation 3 adds residential BESS, PV, and V2G. The formulations are further detailed in Section 4.2.

Section 4.1 presents the objective function to be solved, and the constraints. Section 4.2 describes the different formulations and respective scenarios the optimization simulated. Section 4.3 outlines the model setup and the assumptions made in formulating the scenarios and model environment. Section 4.4 outlines the methodology for solving the optimization. This chapter contributes to accomplishing RO1.

The key concepts and contributions of this research throughout all formulations are the analysis, and insights gained thereof, of:

- The extent of benefits of optimizing the charging scheduling of individual BEV users based on their travel itineraries.
- The effects of different configurations of the residential energy system on the extent of benefits.
- The distribution of the benefits across different travel pattern characteristics and demographic characteristics.

4.1 Objective function and DST

The objective function is the argument of the minimization:

$$\min_{Q_t, t \in \{1 \dots T\}} \sum_{t=1}^T C_t Q_t - R_t G_t + 0 * HV_t + 0 * VH_t + B_t GH_t - I_t HG_t + 0 * HS_t + 0 * SH_t + F_t Y_t \quad [1]$$

with respect to decision variable $Q_t, G_t, VH_t, HV_t, GH_t, HG_t, SH_t, HS_t, Y_t$. The decision variables are at each time interval t . Time resolution of 1 minute was used. Each stay and trip in the trip itinerary were

attached intervals of t . The stay refers to instances when the BEV is parked, and trip refers to instances when the BEV is travelling to and from locations.

For charging amount Q_t with cost C_t and connection cost F_t , defined by binary variable Y_t which is =1 when $Q>0$, with respect to decision variable Q_t, Y_t , and V2G discharge G_t with revenue R_t , transfer of electricity to and from BEV and home VH_t and HV_t , import energy from grid to home GH_t at cost B_t , and export to grid, HG_t with income I_t , transfer of electricity to and from BESS, HS_t and SH_t , with an exogenous home energy demand H_t . The objective function includes the binary variable and connection cost, however, the connection fees were not used in the simulations, and set to 0. However, the MATLAB code produced in this research has the capability to simulate connection fees, and in future works could be used to include this extension.

The objective function is subject to the following constraints:

- $soe_t^{BEVD} \leq soe_{cap}^{BEV} \forall t$; the amount of energy in the BEV cannot exceed the maximum battery capacity and cannot be negative.
- $soe_t^{BEVD} \geq d_t * f_t \forall t$; the BEV must have enough energy in the battery to at least complete its next trip where soe_t^{BEVD} is the amount of energy with which the EV ends stay at time t , and d_t is the distance of the subsequent trip needing to be completed.
- $Q_t + G_t \leq P_t^{BEVmax} * dt_t \forall t$; the charging and discharging rate cannot be greater than the maximum power rating of the BEV.
- $HG_t + GH_t \leq P_t^{gridmax} * dt_t \forall t$; the rate of energy transfer from home to grid and grid to home cannot exceed the power rating at home.
- $VH_t + GH_t + SH_t - (HV_t + HG_t + HS_t) = H_t - PV_t$; the residential energy needs subtract PV generation must be met by the net amount of energy into the home subtract the energy out from the home.
- $HV_t \leq P_t^{BEVmax} * dt_t * EVHyn_t \forall t$; the rate of charging the BEV from the home connection cannot exceed the charging rate of the BEV.
- $VH_t \leq P_t^{BEVmax} * dt_t * EVHyn_t * V2Hyn_t \forall t$; the rate of discharging the BEV to the home connection cannot exceed the discharging rate of the BEV.
- $soe_t^{BESSD} \leq soe_{cap}^{BESS}$; the amount of energy in the BESS cannot exceed the maximum battery capacity.
- $soe_t^{BESSD} \geq 0$; the amount of energy in the BESS cannot be negative.
- $HS_t \leq P_t^{BESSmaxin} * dt_t \forall t$; the rate of charging the BESS from the home cannot exceed the charging rate of the BESS.

- $SH_t \leq P_t^{BESSmaxout} * dt_t \forall t$; the rate of discharging the BESS to the home cannot exceed the discharging rate of the BESS.
- $Q_i \leq u_i Y_i$, where $u_i = P_i dt$ for stay i

The important relationships between different variables in the model are:

- $dos_t = D_t - A_t$; the duration of stay of the BEV at time t is the difference between time of arrival, and departure from.
- $soe_t^{BEVA} = soe_{t-1}^{BEVD} - d_{t-1} * f_{t-1}$; the SoE of the BEV at time t is the SoE of the BEV at departure at time t-1 subtract the distance of the upcoming trip multiplied by the fuel economy.
- $soe_t^{BESSA} = soe_{t-1}^{BESSD}$; the SoE of BESS at start of time interval t equals the SoE of the BESS at end of time interval t-1.
- $soe_t^{BESSD} = soe_t^{BESSA} + BESS_{in}^{eff} * HS_t - \frac{SH_t}{BESS_{out}^{eff}}$; the SoE of BESS at end of time interval t is the SoE of the BESS at start of time interval t add the amount of energy charged to the BESS multiplied by the charging efficiency subtract the amount of energy discharged by the BESS divided by the discharging efficiency.
- $soe_t^{BEVD} = soe_t^{BEVA} + BEV_{in}^{eff} * Q_t - \frac{G_t}{BEV_{out}^{eff}} + BEV_{in}^{eff} * HV_t - \frac{VH_t}{BESS_{out}^{eff}}$; the SoE of the BEV at end of time interval t is the sum of the SoE at start of time interval t, and the net amount of energy charged and discharged into the BEV at time t, factored by the charging and discharging efficiency of the BEV.

Figure 4.1 shows how the equation captures the interactions and components of the integrated energy system represented by the conceptual framework, showing the relevant the decision variables for each component. Figure 4.2 shows the flows of electricity between the different components that each variable represents, based on Figure 3.8 presented previously.

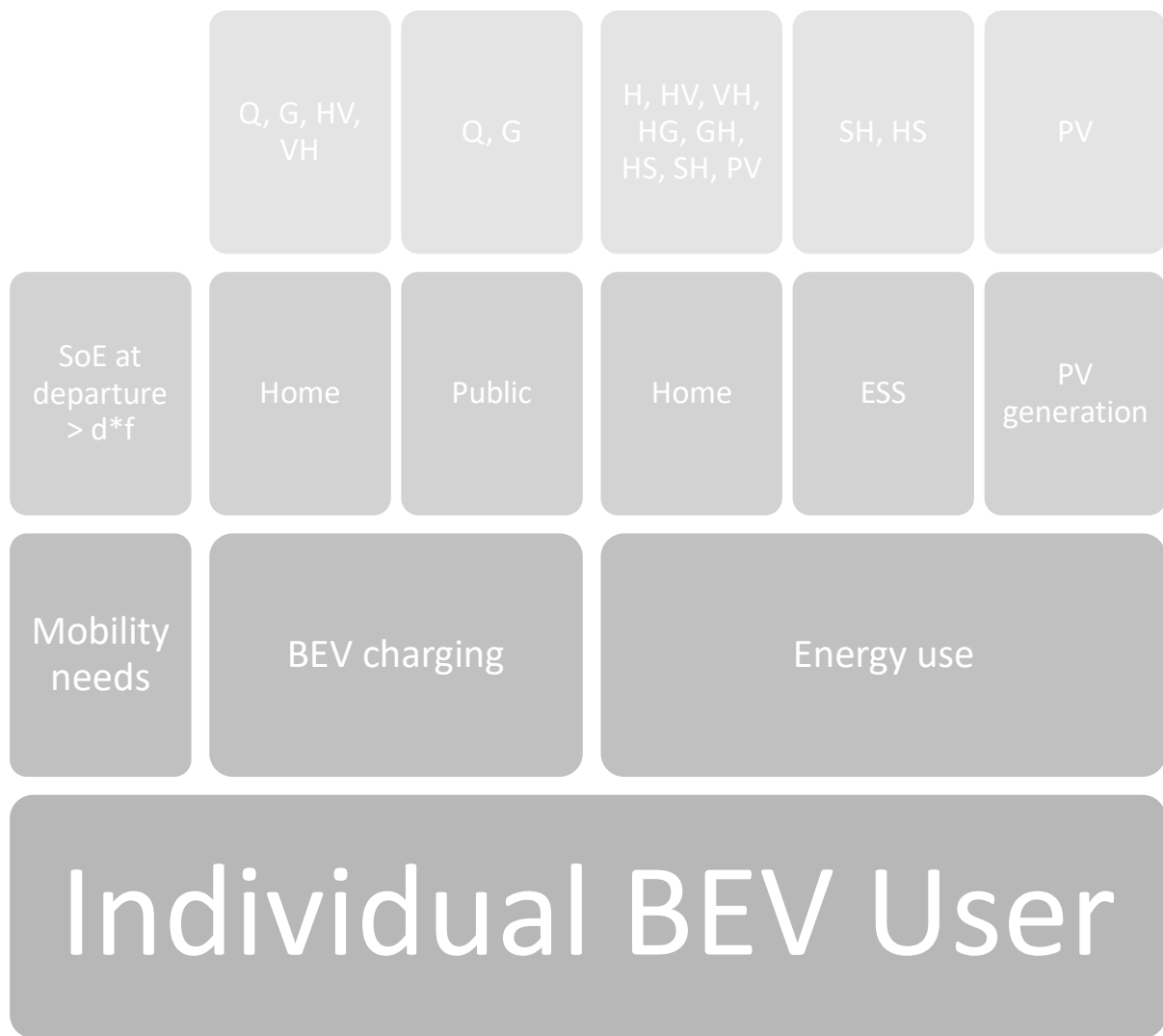


Figure 4.1 How the equation captures the conceptual framework.

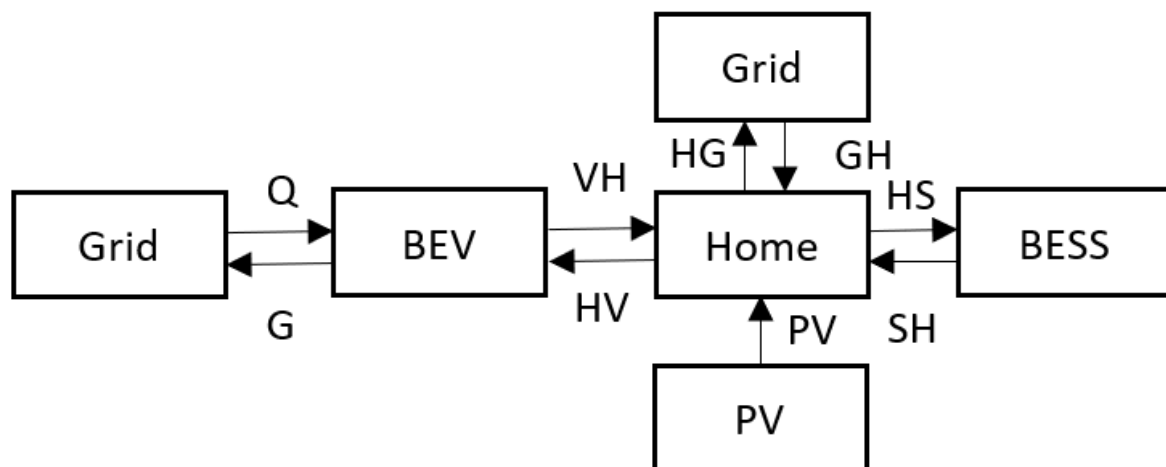


Figure 4.2 The framework and the flows of electricity between the different components of the system represented by the variables of the optimization.

4.2 Formulation & scenarios

The three formulations and their scenarios will be discussed in greater detail in their respective subsections.

Formulation 1 involves optimising the charging scheduling from the individual BEV users' perspectives, based on their detailed travel itinerary, with each trip location having a decision variable for the amount to charge for optimal operating cost. Formulation 1 is important as it builds the foundations for the full framework and allows testing of the benefits of optimizing the charging scheduling on its own merits, and the analysis of the distribution of the benefits. Furthermore, the effect of BEV capacity on the extent of benefits can also be tested. It is the fundamental step of achieving the contributions of this research as outlined in Section 1.3.

Formulation 2 combines the ability of the BEV to act as a MES and interact with the grid and household energy demands through enabling V2H, H2V, and V2H2G. Also included are real-time dynamic TOU tariffs for H2G and residential energy prices. Formulation 2 allows researching the added benefits of enabling BEVs to interact with residential energy, and of dynamic pricing.

Formulation 3 then completes the household energy environment by adding in residential BESS and PV, which is also able to interact with the BEV. V2G is also added, with temporal pricing, to analyse the effects of the BEV interacting with the grid in public. This formulation captures the full framework, and allows testing the intricate system synergies, the distribution of the benefits across demographics, and analysing cost compared to benefit, and the financial accessibility of the low carbon transitions, aiding in achieving the contributions of this research as outlined in Section 1.3.

4.2.1 Baseline “dumb charging” scenario

For all the results in all the scenarios and formulations, a baseline is used to compare the benefits of the optimization against. The operating cost of the optimized case is compared to cost of the baseline. The baseline is desired to represent a simple charging style of charging as much as possible at each available location with no consideration for the cost. This style of charging of this is often referred to as “dumb” or “uncoordinated” charging in the literature. In this research, the optimization is compared to the dumb charging baseline as uncontrolled charging is still the standard in many countries (van der Meer *et al.*, 2018). This style of charging represents the risk adverse nature of users

who wish to always ensure they have enough SoE to meet their mobility needs. This implies that the individual will aim to start the first trip with as high SoE as possible.

The baseline in this research is defined as charging at each stay to the maximum of either the capacity of the EV, or for the DoS multiplied by power rate i.e., the maximum chargeable. The charging amount of the baseline is capped to the full amount of energy needed for the travel itinerary. The capped charging constraint is chosen as it enables like for like comparison between the baseline and optimized cases in terms of the total energy charged. As an example of the baseline, if the total distance for a travel itinerary is 50km, requiring 7.4kWh for the Nissan Leaf, in the baseline, up to 7.4kWh would be charged and no more. The charging events would be spread out as follows. If there are two stays, the first stay 30 minutes long with a 7kW charger, and the second stay 2 hours long with a 22kW charger, 3.5kWh would be charged in the first stay (0.5 hours multiplied by 7kW), then the remaining 3.9kWh in the second stay. Thus, the maximum chargeable is charged at each stay, capped to the total energy requirement. The costs of each charging are calculated by multiplying by the per kWh price.

4.2.2 Formulation 1: optimization of charging scheduling for an individual's total BEV energy charging needs in public and home based on full day travel itinerary detailing each trip

Formulation 1 captures the total energy needs of the BEV in meeting the mobility needs of the user, optimizing the charging scheduling of the complete travel itinerary; the amounts to charge during each stay is the decision variable. Unlike previous studies (Wi, Lee and Joo, 2013; Munkhammar *et al.*, 2015; Alirezaei, Noori and Tatari, 2016; Wu *et al.*, 2016; Wu and Sioshansi, 2017; Ferro *et al.*, 2018; Thomas, Deblecker and Ioakimidis, 2018), this formulation accounts for both home and out of home charging, thus optimizing for the total charging demands. This eliminated the short-sightedness of optimizing charging only for home and leaving the charging in public as a separate problem to be dealt with, with no regard for the displacement of the necessary energy demands and cost of it. Similarly, only optimizing for the public charging, and not considering that once the BEV arrives at the home, it may still need to charge to ensure meeting of further mobility needs, but the price may be more to charge at home than in public. The capturing of the total charging demands extends to Formulations 2 and 3, as the conceptual framework extends and integrates into the energy system via interactions with V2G and V2H.

Figure 4.3 represents the energy flows that the general optimisation problem seeks to optimise, capturing a subset of the conceptual framework for Formulation 1. The only decision variable involved in this formulation is Q , which pertains to BEV charging at home and in public. Figure 4.4 shows the subset of the energy flows of the full conceptual framework that is captured by Formulation 1.

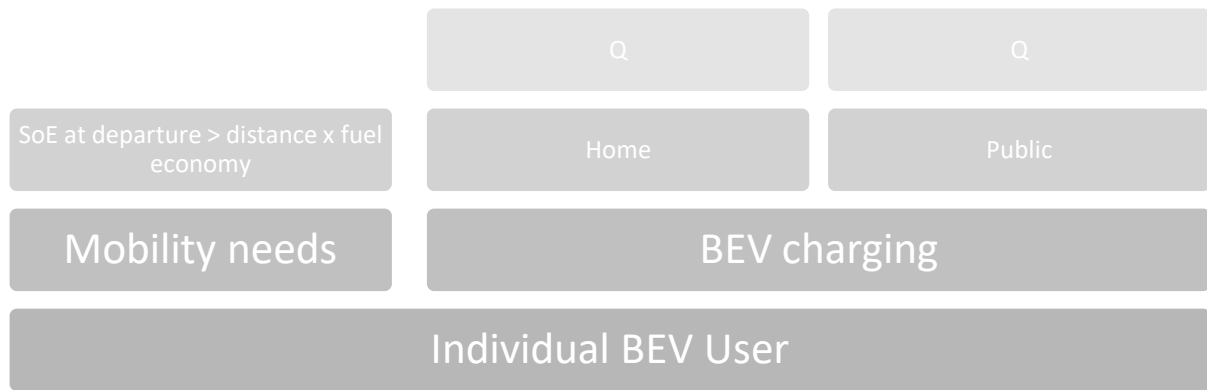


Figure 4.3 How the equation captures apart of the framework for Formulation 1.

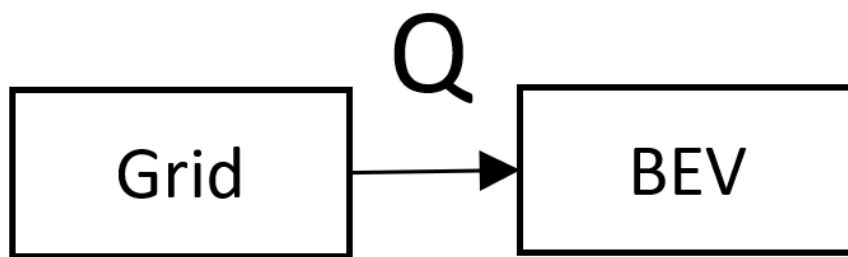


Figure 4.4 The subset of the full framework captured in Formulation 1

Formulation 1 enables answering of research questions, hypotheses and research questions outlined in Section 2.4 and Subsection 3.4.1.: RQ1, RQ3, Hyp1, Hyp2, Hyp3, Hyp4, PQ4, PQ5

4.2.2.1 Scenarios

In Formulation 1, there are nine scenarios. These capture the different scenarios the BEV models and length of optimization time horizon covers. These scenarios enable addressing the research questions as outlined directly above. Four scenarios are based on the four different BEV models. The other five scenarios are based on different optimization time horizons. One scenario takes the Nissan Leaf for a 3-day optimization time horizon. Further four scenarios take each of the four BEV models for a 5-day time horizon.

These scenarios are further detailed below in the following subsections.

4.2.2.1.1 Testing the benefits of optimizing compared to baseline

Of interest was the analysis of the extent and distribution across demographics of benefits of individual BEV users optimizing their charging scheduling in a holistic manner that captures their total BEV energy needs for a full day mobility needs for charging taking place at home and in public. The effects of BEV user travel pattern characteristics were also of interest. Thus, the answer to the impacts

of optimizing for the full BEV energy demands based on the detailed travel itinerary of the BEV users was sought. Unlike many previous studies which have optimized the charging scheduling of BEVs in public in isolation, or at home in isolation, this scenario optimizes for the full charging needs. This allowed answering whether it was beneficial to consider a holistic perspective.

This would also provide results to which comparison for the benefits of adding on other elements of the system could be based.

4.2.2.1.2 Effects of BEV specifications

Four different BEV models are tested by four scenarios. The objective is to assess the effect of BEV specifications on results. The main BEV model chosen for analysis is the Nissan Leaf. Two further models are chosen whose specifications differed either in fuel economy, or battery capacity, whilst keeping the other as close to the Nissan Leaf specifications as possible. The reason for this is to control for the two variables. A further BEV model was chosen which represented the current higher specification BEV technology. For this, the new Tesla Model Y was chosen, which started deliveries in 2020.

4.2.2.1.3 Effects of longer optimization time horizon with 3-day and 5-day

The research hypothesises optimizing over a longer time horizon would achieve higher financial benefits. Therefore, scenarios with three- and five-day optimization time horizons were constructed. The longer time horizons would allow users to capitalise to a greater extent on cheaper charging prices available, by charging a greater portion of their energy demands at the cheaper prices. As the range of most driving schedules is covered by the battery capacity of BEVs, most users would be able to charge the majority of their energy demand at cheaper prices.

Given that a DST would already aid in condensing the information for users to process, there would be no further difficulty for users in handing over the decision making for longer time horizons. Multiple day optimization scenarios were formulated, where each user specific travel itinerary was repeated for the length of the time horizon, as per assumptions in Subsection 4.3.1.

4.2.3 Formulation 2: extension to include H2V, V2H, and household energy demand

Formulation 2 extends upon Formulation 1 by integrating the BEV with the energy system. The integration is achieved through including charging the BEV via home electricity supply at residential energy prices (H2V), V2H, H2G, and residential energy demand. This enables the analysis of the extent of financial benefits to BEV users of integrating their energy system to include BEV charging and discharging at home via the residential electricity connection. Further intricacy within the system is

added through half-hourly dynamic TOU energy tariff for both importing and exporting from the home to the grid. Sensitivity of results to pricing is gauged through analysing different pricing scenarios. The integration allows optimizing the total operating energy cost of the BEV users including their household demand cost. The holistic optimization captures and optimizes the real-world possibility of the BEV importing in energy from opportune public charging to supplement household residential demand, or sell back to the grid, depending on which is preferable, by V2H.

The scenarios to be tested are different combinations of enabled or disabled V2H, H2V, H2G, and the different pricing scenarios, with the different combination of BEV models.

Figure 4.5 represents the subset of the full conceptual framework captured in Formulation 2. The decision variables involved in this formulation are Q , HV , VH , HG and GH , which pertains to BEV charging at home and in public, discharging at home, and the transfer of energy between the home and the grid for meeting the residential energy demands. Figure 4.6 shows the subset of the energy flows of the full conceptual framework that is captured by Formulation 2.

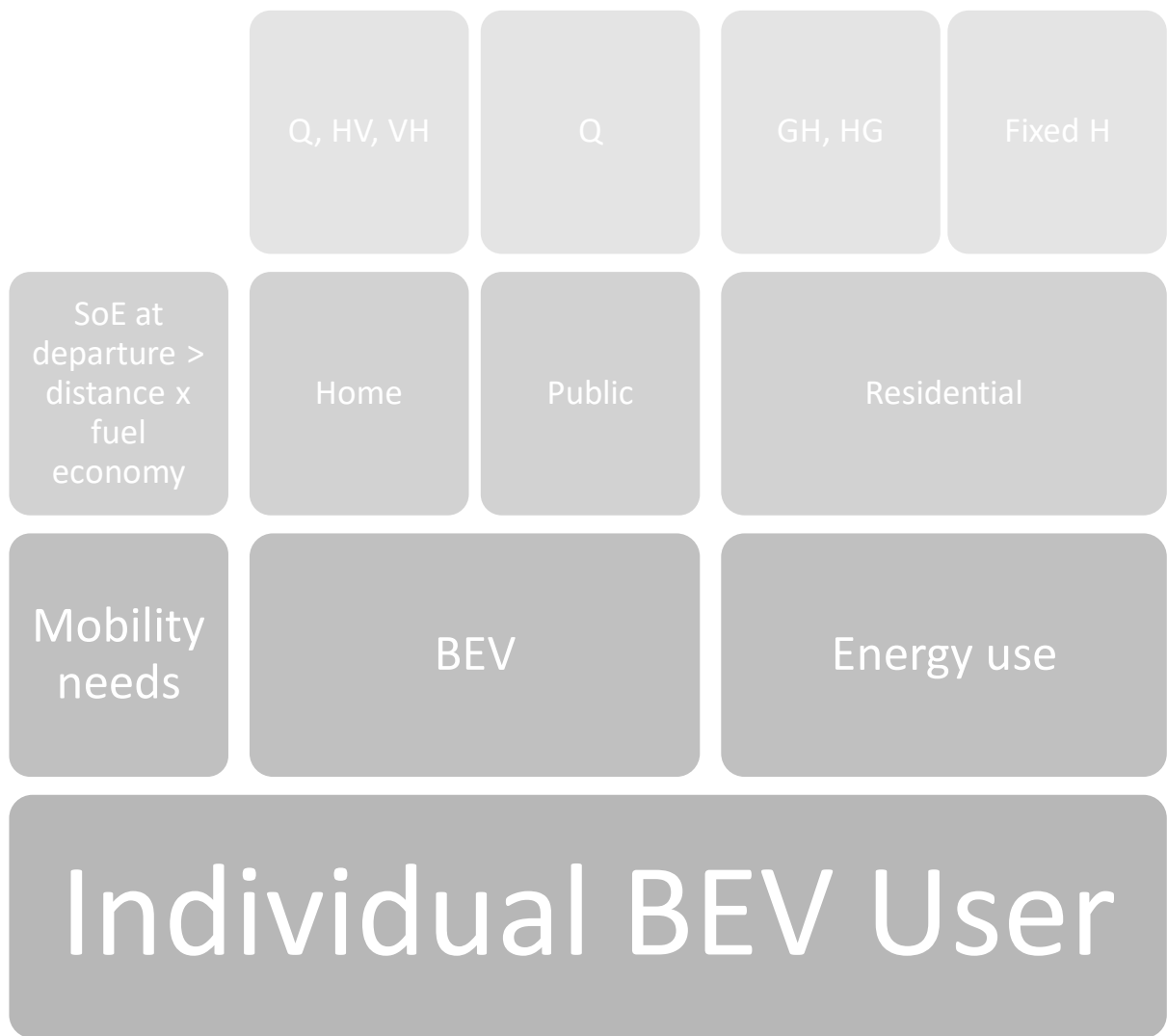


Figure 4.5 How the Formulation 2 captures a part of the full conceptual framework.

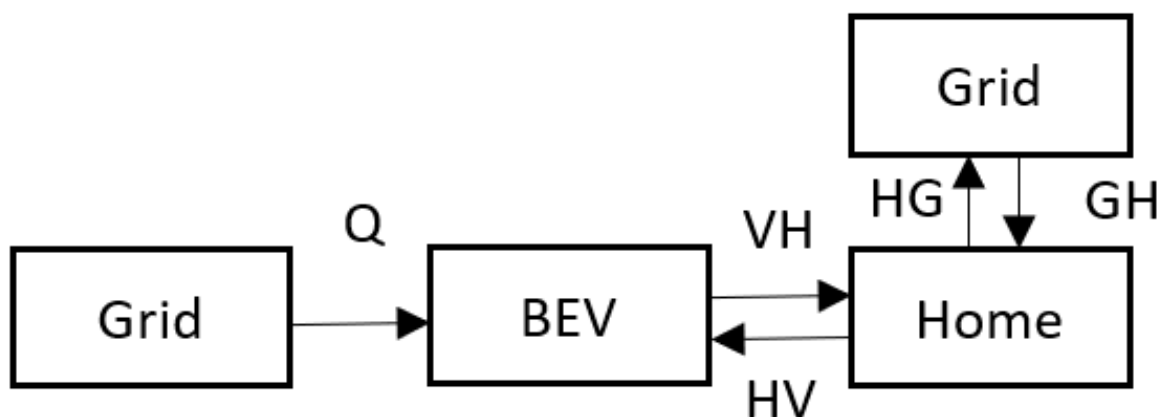


Figure 4.6 Subset of the full conceptual framework captured by Formulation 2, and the flows of electricity between the different components of the system.

Formulation 2 enables answering of research questions, hypotheses and research questions outlined in Section 2.4 and Subsection 3.4.1.: RQ2, RQ3, Hyp5, Hyp6, Hyp7, Hyp8, PQ2, PQ5

4.2.3.1 Scenarios

In Formulation 2, there 144 scenarios. 140 scenarios are 1-day, and four are 5-day.

The 140 1-day scenarios test all possible combinations of the four BEV models, enabled H2V, V2H, H2G, four different residential energy tariff scenarios, and three different pricing scenarios for H2G.

The four 5-day scenarios are for each of the BEV models, where all energy transfers are enabled, with averaging pricing.

Redundant scenarios are excluded. For example, there are no scenarios of disabled H2G with the different H2G pricing scenarios, as in these cases, the results for the different pricing scenarios would be identical, since H2G is not enabled.

These scenarios are further detailed below in the following subsections.

4.2.3.1.1 Combinations of H2V, V2H, H2G and dynamic TOU energy prices

To answer the questions for Formulation 2, the scenarios tested were different combinations of the different interactions of the BEV with the residential energy system added on in this formulation. These allow for analysis that controls for each component and considers the potential synergies between them. The effects of different energy pricing were also of interest. To that end, several pricing scenarios were tested. There were four residential energy pricing scenarios: fixed, dynamic TOU half-hourly (with low, average, and high). The dynamic TOU half-hourly H2G prices had three scenarios of low, average, and high. These are detailed further in Subsections 5.1.4 and 5.1.5 respectively.

The benefits of having access to charging at home was also of interest; specifically, having the option to charge at the cost of electricity from home energy supplier (H2V) as an additional different charging price compared to only having access to public charging prices. This has implications for BEV users who may wish to invest in getting a charger at home, and for policy makers to consider making home chargers more available.

4.2.3.1.2 Multi-day scenarios

The objective of these scenarios is to analyse whether a longer time horizon planning of charging scheduling is more beneficial, and the effects of BEV specifications together with longer time horizons, and the synergy with the different BEV specifications. The differences between benefits for multi day with the energy flows can be compared to the differences between benefits for multi day from Formulation 1 to see if there are additional synergy for benefits through the integrated energy system.

4.2.4 Formulation 3: extension to include BESS, PV and V2G

Formulation 3 extends upon Formulations 1 and 2 by adding the components of residential BESS and PV, and V2G, completing the conceptual integrated energy system framework as proposed by this research. This enables the analysis of the extent of benefits to BEV users of integrating their energy system to include BEV charging discharging in public (V2G). This captured the possible energy flow between the possible components, with the potential for BEVs to act as deferrer of energy demand in space and time through its mobility and storage capabilities. For example, if beneficial in the long term, the PV would charge the BESS even when PV generation does not exceed residential energy demand, to then charge the BEV later, which would then leave at the planned time of departure and be able to receive income through V2G at a higher income than the cost saved through the PV supplementing residential energy demand initially. The utilisation of PV to meet both residential and BEV energy demands, as well as deferred utilisation through BESS and BEV storage can be analysed. The BESS allows extra storage capacity for energy the BEV can bring in. Excess PV could be stored to provide V2G in public.

The scenarios tested are the different combinations of BESS, PV, V2G, and the different pricing scenarios. As mentioned in the literature review Section 2.2, V2G for retail customers is deemed to be for a possibility further into the future. There is uncertainty of how it may be implemented, and in what format it will be available to individual people. Nonetheless, analysing the potential of V2G was desirable and interesting as it adds another level of integration between the grid and BEV. To reflect these uncertainties and timeline, in this research testing V2G in a few scenarios was decided, that represent a world further into the future.

Figure 4.1 represents the energy flows that the general optimisation problem seeks to optimise, capturing the full conceptual framework. The decision variables involved in this formulation are Q , HV , VH , HG , HS , and SH which pertains to BEV charging at home and in public, the transfer of energy between the BEV and home, the transfer of energy between the home and the grid, and transfer of energy between home and BESS. The PV generated electricity first enters the home and is directed accordingly by the optimization. Figure 4.2 shows that Formulation 3 captures the full conceptual framework of this research. The flows of electricity between the different components, and their labels, can be seen in the figure.

Formulation 3 enables answering of research questions, hypotheses and research questions outlined in Section 2.4 and Subsection 3.4.1.: RQ2, RQ3, Hyp9, Hyp10, Hyp11, Hyp12, PQ3, PQ5

4.2.4.1 Scenarios

In Formulation 3, there are 1,324 scenarios. 1,314 of them are 1-day scenarios. 10 are 5-day scenarios. 1,308 scenarios are with the Nissan Leaf, for combinations of energy transfers (V2H, H2V, H2G, but excluding V2G), pricing scenarios, four different BESS sizes including 0 (no BESS), four different PV sizes including 0 (no PV), and two PV seasons. Only the Nissan Leaf is used, as Formulation 2 tested the effects of BEV specification, therefore additional effects of PV and BESS can be assessed whilst holding the BEV specifications constant. A further four scenarios are with the Model Y with all energy flows (excl. V2G) enabled, with combinations of two of each BESS and PV sizes; larger PV and BESS sizes are introduced, not used with the Nissan Leaf. The objective of this is to assess potential future cases of greater BESS and PV sizes made available through advances in technology.

The eight of the 10 5-day scenarios are with the Nissan Leaf and Model Y, with all energy flows (excl. V2G) enabled, with the same two PV and BESS sizes as used for the Model Y 1-day scenarios. Only Nissan Leaf and Tesla Model Y are tested, as the effects of BEV specifications could be tested in the previous formulations.

Four scenarios with V2G were tested. These have all components enabled and uses the Tesla Model Y. Two scenarios as 1-day and two as 5-day, each with one scenario with the smaller BESS and PV sizes, and the other with the larger sizes introduced for the Tesla Model Y as previously mentioned.

Redundant scenarios were excluded. There are no scenarios where PV size was 0 (no PV), with different PV seasons. The results for the different pricing scenarios would be identical since PV has no energy output regardless.

These scenarios are further detailed below in the following subsections.

4.2.4.1.1 Combinations of PV and BESS

To answer the research questions with Formulation 3, the scenarios to be tested are different combinations of the PV and BESS added on in this framework, along with the different components added on in Formulation 2: H2V, V2H, H2G and temporally varying energy prices. These allow for analysis that controls for each component and one that also considers the potential synergies between them. To test for sensitivity to PV generations, two scenarios of PV generation were considered: summer and winter.

4.2.4.1.2 Multi-day scenarios

The objective of these scenarios is to analyse the effects of longer optimizing time horizons, BEV specifications, and larger PV and BESS.

4.2.4.1.3 V2G

To analyse a potential representation of the world further into the future where V2G is widely available, scenarios are tested where all other components were available, for the Tesla Model Y specifications to represent higher specifications in the future, with the V2G added on. This allows analysis of the added benefits of V2G and potential synergies whilst controlling for it.

4.3 Model setup and assumptions

This section details the model setup and assumptions for the optimization. The details included here apply to all three formulations. This section discusses which types of data and parameters were used, and how they represent the real world. The author acknowledges that some of the assumptions taken in this research will be an incomplete representation of the real world. Nonetheless, the methods and contributions of this research will provide useful insights and analysis of integrating the energy system with the basis around mobility needs. The specific values for parameters are discussed in Section 5.2.

4.3.1 Travel itinerary

The travel itinerary for the BEV user represented their travel needs and schedules. It was used to characterise individual's travel patterns. The travel itinerary for this research was taken from the London Travel Data Survey and will be discussed further in 5.1.1.

The difference between the trip end and next trip starting times was taken as the DoS. The difference between the trip start and end was taken as the DoT. The trip distance multiplied by the BEV fuel economy was the energy needs for the respective trip.

The parking type and land use types as per the travel itinerary was used to attach trip location specific charging prices. This is further discussed in Subsection 5.1.1.

The travel itinerary was taken exactly from the travel and, and the constraint of BEV user not changing their mobility patterns/trip itinerary was placed. The stochastic behaviour of drivers was neglected; this assumption has also been made in previous studies (Salpakari *et al.*, 2017; Mozafar, Amini and Moradi, 2018). Perfect information was assumed in a previous study (Salpakari *et al.*, 2017), and noted

that the results therefore represent the upper limit, with limited forecast horizon and accuracy in actual implementation; the analysis of effects of forecast horizon and error with available forecasts were left for further work.

For multi day simulations, the 1-day travel itinerary input data was replicated for the number of days of the optimization time horizon. The assumption of perfectly repeated travel itineraries is not a fully accurate representation of the real world. Total variability in time allocation for activities for a person was found to be roughly constant for an individual across the weekdays, however, the variability in number of trips per day during the weekdays for an individual was found to be higher than the variability across individuals (Raux, Ma and Cornelis, 2016). A study of travel data in Los Angeles concluded that travel activities of individuals may not be repetitive on a daily basis (Li *et al.*, 2018). Whilst the assumption of perfectly repeated travel itineraries is not perfect, the question to be analysed was whether planning for more than a day ahead would yield change the extent of benefits. Thus, the exact repetition of travel itinerary is in fact an appropriate control to have, as only the effects of a longer time horizon analysis will be analysed, without interference from the effects of different travel patterns. A one week travel data was duplicated to make align with a two week time horizon analysis (Aguilar-Dominguez, Dunbar and Brown, 2020).

Travel patterns for BEV users were assumed to be similar with that of traditional ICEV users. This assumption is relevant for the input travel data. It was indeed noted that travel patterns of EV users were similar with that of traditional ICEVs (Nunes, Farias and Brito, 2015; Hardman *et al.*, 2018).

The charging demand was assumed to be constant across seasons. No significant variance in charging behaviour was found across seasons (Quirós-Tortós, Ochoa and Lees, 2016).

Each person was taken to be from a unique household, even if from a household of multiple people, and their travel itinerary taken in isolation. Therefore, the savings for that person is that person's own, even if the household has more people living in them, and the overlap of multiple BEV users belonging to a single household is not taken into account. Thus, overlap or activities and savings is not considered, such as one person doing the driving to shop for multiple people.

4.3.2 BEV public charging

The public charging of BEVs was an important component of the model setup.

Different charging prices and power ratings were set at different land use and parking types provided in the input travel data. This reflects the real-world variation in charging prices. Some types had free charging. This is further discussed in Subsection 5.1.2.

EVSE was assumed available at each stay, always giving the BEV an option to charge. There is no consideration of competition between users, or unavailability of EVSE. It is acknowledged that this is a major assumption. However, this assumption will become more realistic as more and more EVSE are installed in the future, both to give enough charging spots at each location, and availability in more locations.

As EVSE was always assumed available, all charging demand at each EVSE was met, provided there was sufficient time to transfer the energy, given the respective EVSE power rating.

The possible duration of charging was equal to the DoS; time taken to connect and disconnect to the EVSE was taken to be negligible. This simplification has some lenience as the travel data is accurate to the minute, thus some time is rounded within the data itself. This is in part justified from the fact that an extra minute of charging will not significantly impact the overall amount of energy charged within the itinerary. However, it is acknowledged that for short DoS, the time for connection which is neglected would represent a greater proportion of chargeable time.

A minimum DoS of five minutes for charging to be allowed was set to stop the optimization allowing unrealistic and unreasonable charging events occurring during very short stays.

4.3.3 BEV models and specifications

BEV specifications and assumptions made regarding BEVs are discussed in this subsection.

The four BEV models chosen were the Nissan Leaf, Hyundai IONIQ, MG ZS, and Tesla Model Y. The Nissan Leaf was chosen as it is a very widely sold model. The Hyundai IONIQ and MG ZS were fitting specifications for the sensitivity analysis of BEV specs. Model Y was chosen as the state-of-the-art and yet affordable BEV. The specifications are further detailed in 5.2.1.

The BEV model specifications to be tested were based on real BEV models to be able to test for real specifications that exist and are purchasable. The analysis of the effects of the BEV specifications could be generalised and be applicable to other BEVs and their specifications.

To test and control for the effects of BEV model specifications, for each scenario, the same BEV model specifications were applied to all drivers.

The fuel economy of the BEV was assumed to be constant. This was adopted in a previous study (Salpakari *et al.*, 2017).

Roundtrip efficiency of the BEV and BESS batteries are further detailed in 5.2.1 and 5.2.7 respectively.

Cyclic damage and battery degradation are taken as negligible; in this model, there is no decreasing of BEV battery capacity, or cost consideration of battery degradation. An accurate analytical equation to define battery degradation is difficult due to many factors influencing it, and large uncertainties and non-linear relationships between them (Wang *et al.*, 2017). There are contrary opinions in the literature regarding the significance of considering this factor. Frequency regulation and peak load shaving at typical power rates for vehicle charging and discharging was not found to significantly increase battery degradation on top of the degradation from driving (Wang *et al.*, 2016). The capacity losses from frequency regulation and peak load shaving were 3.62% and 5.6%, respectively, for 10 years of daily grid services between 7-9pm. On the other hand, the lifetime of batteries for vehicle use was found to potentially be shortened to less than five years due to additional cycling to discharge vehicle batteries to the power grid, even at constant power (Dubarry, Devie and McKenzie, 2017).

It can be argued that whilst degradation exists, the optimization may not cause a detrimental effect. Thus, the cost implications could be no worse normal charging operations. This was evidence in a study that showed that nominal charging case had similar battery degradation effects with various different charging and discharging strategies, and that battery degradation at rest was found to be the dominant form of degradation (Thompson, 2018).

Due to a lack of coherent and agreeing opinion, and the fact that this is not the major component of the contribution of this research, it was chosen to be taken as negligible.

4.3.4 Residential energy demand

The residential energy demand used in the research applied the same profile to each household which was then factored by the household size, to account for greater demand based on occupancy. This is detailed further in 5.1.3.

It was assumed that all households had the same energy demand profiles, as well as the same overall demand given the same number of occupants. It was assumed to be independent of any BEV energy usage. Variability in profiles of homes in Texas with BESS was analysed using principle component analysis and identified a total explained variance of 78% in principal component 1 and 2, and it was reasoned that variance in BESS discharging is related to the home user's behaviour (Mabuggwe and Morsi, 2020).

4.3.5 Residential energy pricing

Four different residential energy price scenarios were used: fixed (constant price throughout the day), and 3 dynamic TOU (average, low, high). In this thesis, half-hourly real-time dynamic TOU electricity tariffs were used. Many studies in the literature used TOU in their models, but their tariffs only consisted of several (around 2-5) different price points. In this thesis, there are 48 different price points throughout a day. There are energy providers who provide dynamic TOU energy tariffs, and this is captured by the pricing scenarios. These are detailed further in Subsection 5.1.4.

Energy pricing across different households was assumed to be homogenous. In reality, there would likely be variability between households due to being with different energy providers, or neighbourhood.

4.3.6 Home charging (H2V) and V2H

In some scenarios, the energy flow from vehicles to homes are enabled. This captured the ability of BEVs to charge bi-directionally for this model.

Home charging, or H2V, captured BEVs charging through home charging infrastructure with residential energy prices for users who have their own private parking area and have home charging infrastructure installed, and thus bill their BEV charging demands to their residential energy demand.

V2H allowed BEVs to supplement residential energy demand through their energy storage capabilities. There are two ways of doing so. In one way, they could use the energy charged in public to supplement the residential energy demands, if the energy charged in public was at a lower cost, thus acting as a MES. In another way, whilst parked, the BEV could store energy at times of lower cost, then discharge back at times of higher cost to displace temporally the cost of energy from high to low.

H2V and V2H was only possible for households with access to their own private off-street parking could have charging infrastructure installed which would allow BEVs to be charged from the residential energy plan and have bi-directional energy flow. It was assumed that in scenarios with H2V or V2H enabled, all households with such access had such infrastructures and thus H2V and V2H were possible.

Scenarios in which V2H was enabled, H2V was also enabled. The reason for this is that a real-world case where the technology for V2H exists, and H2V does not, is not foreseen. That is, if there is a BEV, it must always at least be able to charge from the home (H2V), and it may or may not be able to bidirectionally charge back to the home (V2H).

4.3.7 H2G

Currently, there are limited commercially available H2G options for individuals. However, there is a drive to make this more prevalent. Octopus is an energy provider in the UK which does offer individuals households to partake in H2G, with half-hourly pricing reflecting the wholesale market. This was adopted in the model to reflect an existing, and potentially more widespread availability of H2G, and the way it may operate.

The prices of H2G from Octopus varied day by day, and month by month. To capture the real-world seasonal variations, average, low and high pricing scenarios were used. The different H2G pricing scenarios are detailed further in Subsection 5.1.5.

H2G prices were assumed to be the same for every household.

Energy losses in transfer of electricity in H2G was taken to be negligible.

4.3.8 BESS

Several sizes of BESS were used to reflect the availability of different sizes of BESS. The sizes are within the ranges widely sold in the UK to individual households.

For each scenario of given BESS size, the same size was applied to all households to control for the effects of the size of BESS.

BESS have different power rating for input and output. These were captured within the model to limit the rate of charging and discharging at each time increment.

The efficiency in charging and discharging of BESS was included and assumed to stay constant, and consistent.

Cyclic damage to the BESS was assumed to be negligible.

Further details on the specifications of BESS are in Subsection 5.2.7.

4.3.9 PV

Several sizes of PV were used to reflect the different sizes of PV available to households. The sizes are within the ranges widely sold in the UK to individual households.

Seasonality impacts the amount of energy generated from PVs. To capture this, winter and summer scenarios were tested. These capture both the strength of the radiation coming from the Sun, as well

as the times of the day at which the PVs generate energy. It did not make sense to have an average scenario which averaged the temporal annual PV generation. This would lead to early and late times of the day having the summer PV generation lowered by averaging the other months where there was no PV generation due to the sun not rising early enough. Such days as a data set would not exist in reality, when averaged and considering cloudy days and so on.

For each scenario of given PV size and generation season, the same PV size and overall generation was applied to all households, to control for the effects of PV generation. Every household was assumed to have the same PV generation amount and profile. The correlation of PV generation within regions the size of a borough in London is nearly 1 (Widén, 2011). Variability in profiles of homes in Texas with PVs were analysed using principle component analysis and identified a total explained variance of 84% in principal component 1, and 94% in principal component 1 and 2 (Mabuggwe and Morsi, 2020).

Energy losses in transfer from the PV was assumed to be negligible.

4.3.10 V2G

V2G is an interesting concept which is currently being tested. Therefore, some scenarios were tested with V2G availability. This captured the income BEVs could make through V2G. For the scenarios with V2G enabled, V2G was deemed to be available at every trip location, including at home. This was deemed different to H2G, and instead classified as V2G whilst parked at home, since the household itself is not a source of the energy to the grid, but merely the intermediary from the BEV to the grid.

There are not many options available currently to individual BEV users. Thus, to test the added benefits of V2G, it was tested in such a way that the V2G would be widely available, and in the same pricing format as H2G. V2G was assumed to be available everywhere, and the prices to be spatially constant. The prices for V2G were assumed to be same as for H2G, as a proxy for value to the grid. The H2G prices were interpreted to reflect the value to the grid of grid services, and thus the V2G prices were set equivalently.

There was a possibility of a loophole in the model construction where there may be many instances in a user's travel itinerary where charging cost in public was lower than V2G revenue at the same time instance. Whilst some instances of this may be possible in real world, the occurrences of this within the model was frequent, at any time a car was parked at a free charging location, and V2G was available. To amend this, where cost to charge EV in public was less than revenue from V2G, the revenue was matched to the cost to charge. This means the optimal solution would not be affected by partaking in V2G at such locations.

4.4 Methodology for solving of optimization

The methodology used to solve the optimization is outlined in this section.

4.4.1 Linear Programming

Linear programming (LP) was used to solve the optimization. The full formulation of the problem in this thesis is a mixed-integer linear programming (MILP), as in Section 4.1. In the empirical work of this thesis, it is simplified to an LP by dropping the fixed connection fee binary variable. The binary variable is dropped as CSPs which do not charge a fixed fee were more relevant (pricing of CSP charging are further detailed in Subsection 5.1.2). Furthermore, LP reduces the computational burden significantly.

There is a precedent for LP and MILP being used in previous studies that also sought to optimize energy flows in an integrated system (Erdinc, 2014; Kuang *et al.*, 2017; Salpakari *et al.*, 2017; Doroudchi *et al.*, 2018; van der Meer *et al.*, 2018; Chitsuphaphan, Yang and Dai, 2020; Iria and Soares, 2020; Wang *et al.*, 2020).

4.4.2 CPLEX

The LP was solved using CPLEX solver v.12.9 (IBM ILOG CPLEX Optimization Studio) on MATLAB. CPLEX uses simplex and barrier algorithms to solve linear programs. Previous studies have used CPLEX to solve MILP problems, using CPLEX version 12.9 (Chitsuphaphan, Yang and Dai, 2020), version 12.7 (Iria and Soares, 2020), v.12.6 (van der Meer *et al.*, 2018), v.12.4 (Salpakari *et al.*, 2017), v.12 (Erdinc, 2014), and unspecified version (Wang *et al.*, 2020).

4.4.3 Optimization process

The optimization solved for the time horizon of 1 full day's travel itinerary in a 30-hour horizon for 1 day scenario optimizations, 78 hours for 3 days, and 126 hours for 5 days scenarios. The additional 6 hours were added into each time horizon as some itineraries included trips past midnight of the first day, for example, at 2am after the first full day. The time resolution was 1 minute.

The process involved in the optimization solving on MATLAB using CPLEX can be seen in Figure 4.7. The process involves initialization, followed by loading the data which has been pre-processed previously.

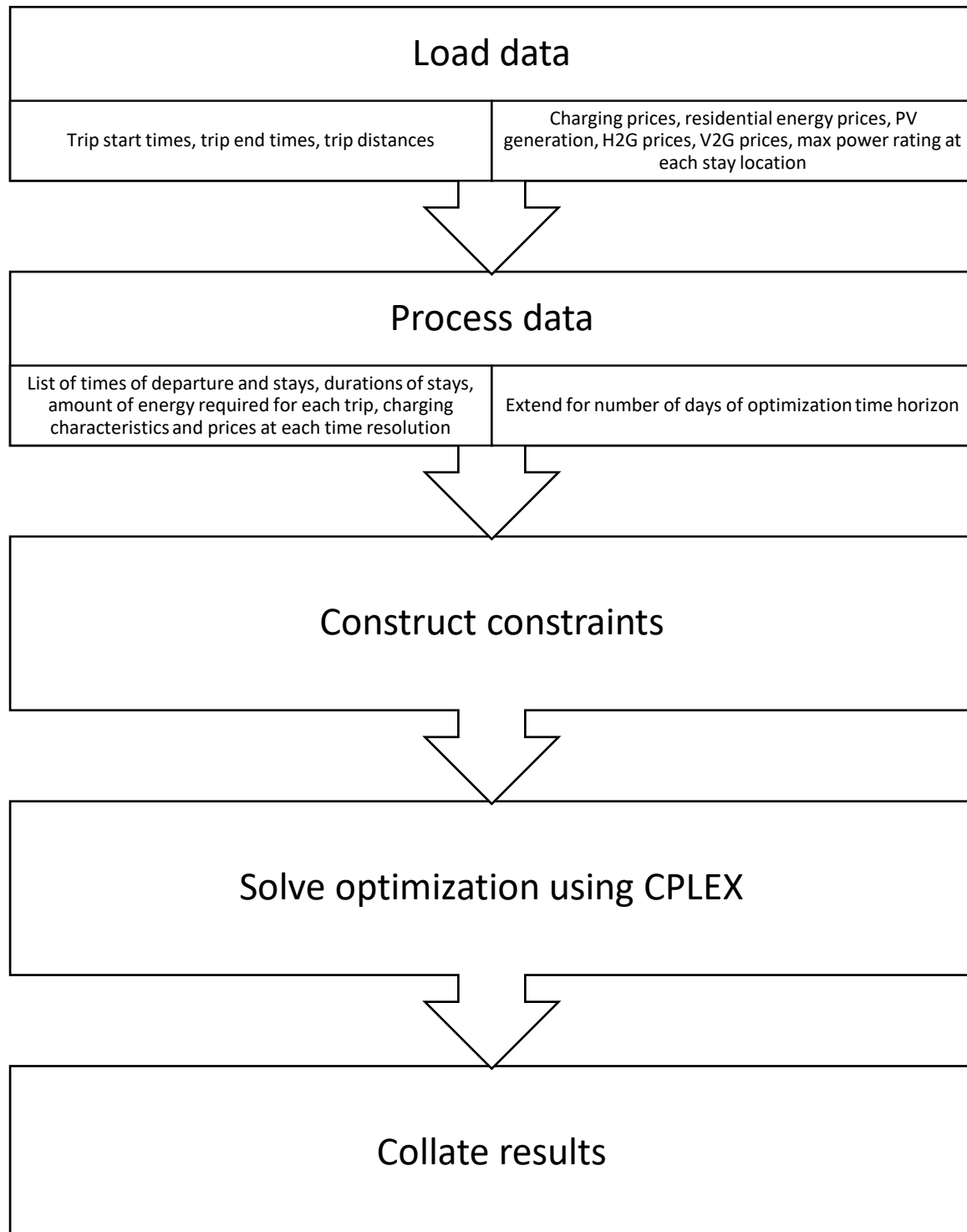


Figure 4.7 Steps involved in the optimization process.

4.4.4 Travel itinerary values calculation

The input travel data was used to calculate various values required for the optimization.

4.4.4.1 *Duration of stay*

The trip start and end times were used to calculate the duration of trips and duration of stays by subtracting the trip end times from start times, and subtracting the subsequent trip start times from the previous trip end times respectively.

4.4.4.2 *Energy required*

The energy required for each trip was calculated by dividing the trip distance by the BEV fuel economy. There is precedent for this basing the energy needs of BEVs on the real travel time durations, times of arrival and departure, and duration of stay from previous studies (Mozafar, Amini and Moradi, 2018).

Chapter 5

Data, parameters, and variables in the scenarios of the model

The optimization required data and parameter inputs. The data needed for the optimization, the collection and selection of the data, the processing, and assumptions about the data in this study are detailed in this section. This chapter also outlines the parameters used in the model. The usage of appropriate data for the optimization model is important such that the results would be based on realistic settings. This would ensure that the analysis of the results would yield insights of the impacts the optimization could have on real-world settings.

Data is needed for each component of the optimization to represent the real-world and make the problem solvable. The input data needed for the full model and their respective subsections are:

- Travel data of individual BEV users to characterise charging needs, times the BEV was parked such that they could charge, and location specific costs at each stay in the travel itinerary
 - Subsection 5.1.1
- Price data for public BEV charging, residential energy tariffs, income for H2G and V2G
 - Subsections 5.1.2, 5.1.4, 5.1.5
- Residential energy demand data
 - Subsection 5.1.3
- PV generation data
 - Subsection 5.1.6

Figure 5.1 shows the data inputs graphically. For Formulations 1 and 2, the relevant subsets of these data are needed.

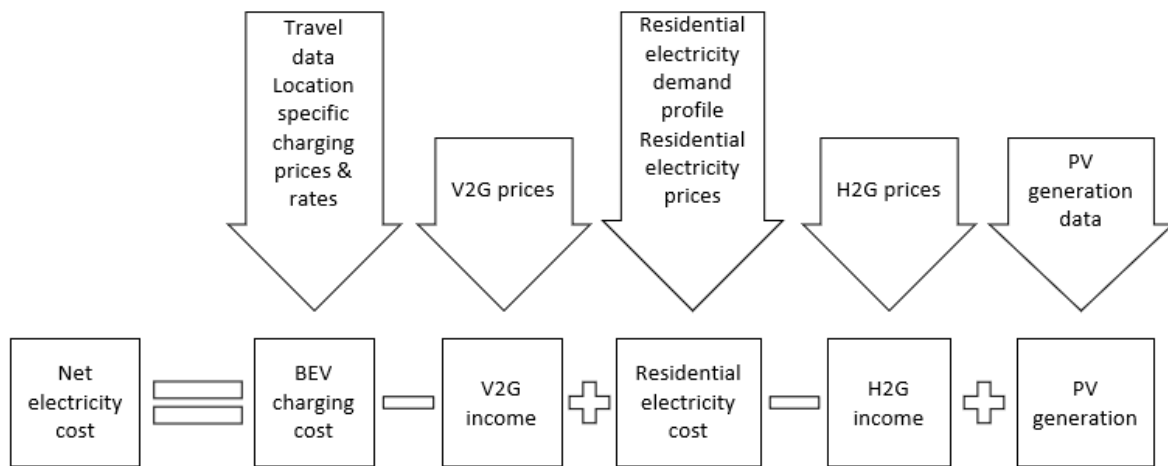


Figure 5.1 Data needed for the optimization.

Whilst a specific set of data were used in this study, the optimization can be applied using other data sets in the suitable format, to analyse the impacts for any travel pattern data, household energy demand, PV generation and so on. The flexibility and adaptability of this model can contribute to creating insights to many other contexts.

Section 5.1 details the data used in the optimization, including the processes involved in data collection, pre-processing, data summary and format and assumptions. Section 5.2 details the parameters used in the model. Section 5.3 discusses the uncertainty in the data. This chapter contributes to accomplishing RO2.

5.1 Data

5.1.1 Travel data: LTDS

The London Travel Data Survey (LTDS) was chosen this research. The reason for using the data, and the processing of the data is detailed in this subsection.

The dataset met the criteria for having trip-level detailed travel itineraries of individuals, showing the times of departure and arrival for each trip, distances, and land-use and parking types of the stay locations. Information on the type of parking at each stay allowed attaching location specific charging prices. LTDS is widely used in research as a set of reliable and representative travel data for London and should be robust for London-wide level. It is one of the most rigorous surveys of its type, conducted by TfL in association with Research International. Other travel survey data similar to LTDS are also used in research, such as the National Household Travel Survey (NHTS) for the US. NHTS, and

other travel survey data has been used in previous studies seen relating to this field of study (Kang and Recker, 2009; Darabi and Ferdowsi, 2011; Green, Wang and Alam, 2011; Mozafar, Amini and Moradi, 2018). The 2015-2016 dataset containing travel itinerary of individual people was used as it was the most recent dataset available at the commencement of the research.

The LTDS dataset was pre-processed, which involved selecting only the individuals who were car drivers (as stated on the LTDS). Car drivers were interpreted to mean those driving their own personal passenger vehicles.

During the pre-processing, datapoints with errors were found and filtered. These were:

- Trip itineraries where any of the trip distances were less than 0km
- Trip itineraries where any of the trip distances were larger than 235km, as exceeded the range of the BEVs used in this model, and would lead to errors
- Trip itineraries where the trip end time was later than the start time of the next trip

The data filtering leading to the final number of individuals' travel itineraries is summarised:

- 13,556 – full data number of individuals
- 3,332 – individuals who are drivers
- 49 – individuals whose trip itineraries had trip distances less than 0km
- 9 – individuals whose trip itineraries had trip distances greater than 235km
- 16 – individuals whose trip itineraries had time errors (2 of which overlapped with trip distances over 235km)
- 3,260 – final set of individuals used in the optimization ($3,332 - 49 - 9 - (16-2)$)

The input data for the optimization required for the optimization and extracted from the LTDS were:

- The start and end times and distances of each trip
- The land-use and parking type of each trip
- The household sizes
- Household access to private off-street parking

Besides data cleaning, the data was pre-processed to prepare it for use in the optimization.

From the data detailing the start and end times of each trip, the respective DoT were calculated. The times of the stays were calculated from the different in time of the end of a trip, and the start of the subsequent trip.

Some trips in the data started immediately after the previous trip, where the end time of a trip and the start time of the next trip were the same. In these cases, the DoS value was adjusted to 1 minute, as opposed to 0 minute.

The type of parking and land-use as stated for each trip in the LTDS travel itinerary were extracted and attached a specific charging price and rate. The specific charging prices and rates and how they were assigned are detailed in 5.1.2 and 5.2.4 respectively.

The LTDS also included data regarding the individual and their household. The extracted data include household size, borough of household, household income, and the individuals' ethnicity and employment status. Some of these data were used in the regression analysis, and further detailed in Section 6.1.

Some assumptions about the data were made. Access to private off-street parking stated in the LTDS was assumed to mean access to a parking area such that home charging infrastructure could be installed and connected to the home energy plan to charge the BEV, such as a driveway or garage.

The LTDS dataset can list multiple persons' trip data under a single household. The trips belonging to each person was taken in isolation. The overlap of multiple BEV users belonging to a single household was not taken into account. Thus, a household with multiple BEVs was analysed as if each BEV belongs to separate household of same characteristics regards to their energy demand, rather than multiple BEVs contributing to the integrated energy system through V2H etc.

There were no households and therefore individuals and their travel itineraries in the borough of Westminster in London in the 2015-16 LTDS dataset.

5.1.2 Public charging prices

To set the appropriate public charging prices, data on charging prices across London was required. Charging prices were collected from the main CSPs in London (Table 5-1). The average price per kWh for each CSP was calculated; monthly membership fees were ignored. The average price across the different providers in London was £0.4139 per kWh.

Table 5-1 shows the different prices available from various charging providers in London. The CSP market is fragmented, and there are many possible prices than individuals could pay depending on the CSP, the payment type, and the charging rate.

Table 5-1 Charging provider price plans in London (Zap Map, 2019).

<i>Provider</i>	<i>Plan</i>	<i>Monthly fee</i>	<i>3kW: Cost per kWh</i>	<i>7kW: Cost per kWh</i>	<i>Connect ion fee</i>	<i>22kW: Cost per kWh</i>	<i>Connect ion fee</i>	<i>50kW: Cost per kWh</i>	<i>Connect ion fee</i>	<i>Averaged Cost per kWh</i>
<i>Polar Network</i>	Polar instant	N/A	£0.1800	£0.1800	£0.00		£0.00	£0.2500	N/A	£0.203
<i>Source London</i>	Full	£4.00	£1.0000	£0.4286	£0.00	£0.2973	£0.00	N/A	N/A	£0.575
<i>Source London</i>	Flexi	N/A	£1.4600	£0.6257	£0.00	£0.3627	£0.00	N/A	N/A	£0.816
<i>Source London</i>	PAYG	N/A	£1.6800	£0.7200	£0.00	£0.4282	£0.00	N/A	N/A	£0.943
<i>Pod Point</i>	-	£0.00	£0.1700	£0.1700	£0.00	N/A	£0.00	N/A	N/A	£0.113
<i>Tesla</i>	Super-charger	£0.00	N/A	N/A	N/A	N/A	N/A	£0.2400	£0.00	£0.120
<i>ESB EV Solutions</i>	EV Solutions	£4.00	N/A	N/A	N/A	N/A	N/A	£0.2500	£0.00	£0.250
<i>ESB EV Solutions</i>	PAYG	£0.00	N/A	N/A	N/A	N/A	N/A	£0.2900	£0.00	£0.290

In the optimization, the charging prices at each stay in the travel itinerary was based on the parking type. Figure 5.2 shows the process used for setting the charging rates. The prices at each location can be seen on Table 5-2.

The parking type determines EVSE the user would have access to and the entity the EVSE would belong to, therefore the appropriate characteristics such as price, rates were based on the parking type. For example, even if the purpose of trip was for work, and thus the land use was office, the type of EVSE will depend on whether they parked on the street, or in a car park.

From the different categories of parking type in the LTDS, public off-street parking was taken to refer to car parks. Private off-street parking to those owned by supermarkets, hospitals, offices, etc.

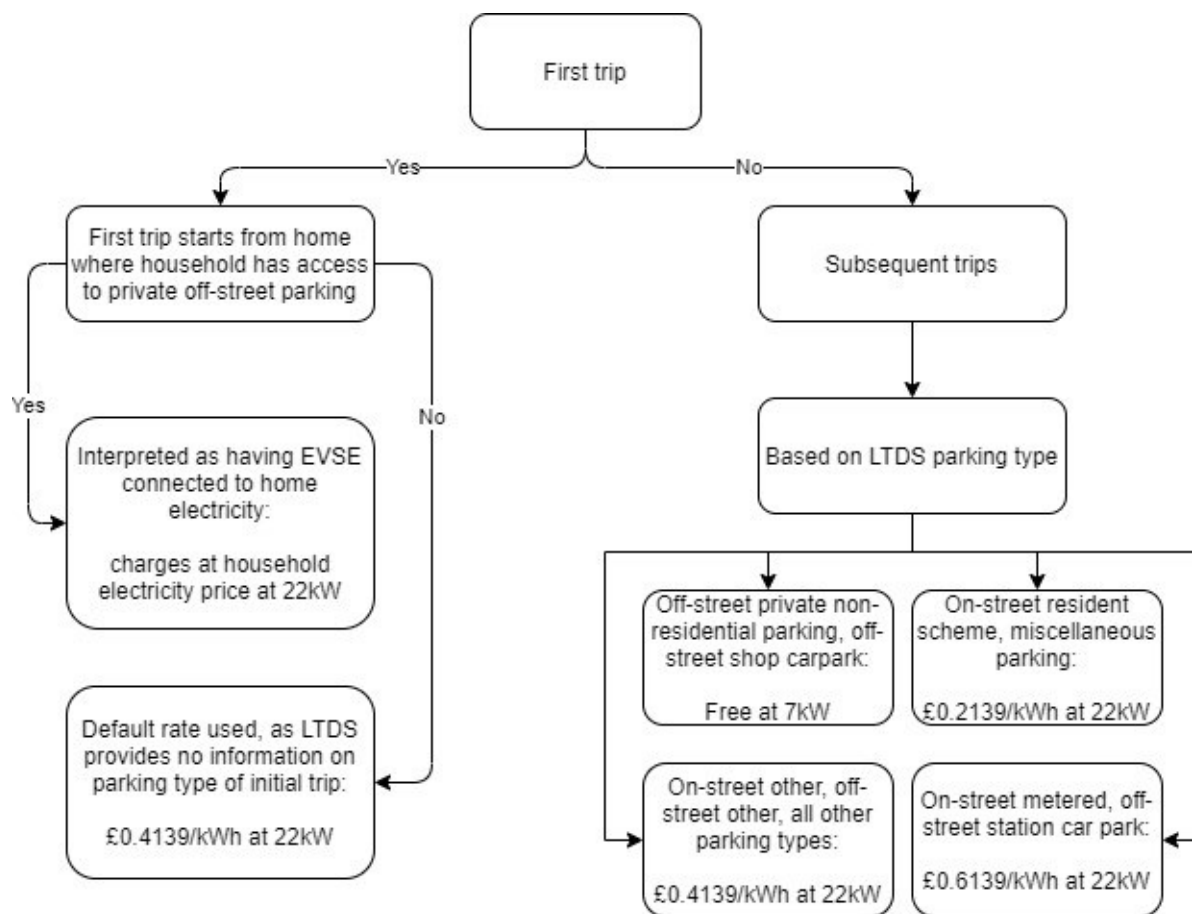


Figure 5.2 Charging prices at locations and selection process hierarchy.

The set of prices were designed to capture realistic settings and trends. The rate for public charging was set at 22kW. The average of prices available in London based on some of the CSPs was £0.4139/kWh. Therefore, public charging through CSPs were set at three different prices based on the average price to capture the variability seen in London, and to diversify the prices for the average high and low-price locations: £0.4139/kWh, £0.6139/kWh, and £0.2139/kWh. The specific parking types for each price are on Table 5-2. This represents the differences in prices BEV users face at different locations due to differences in CSPs.

Supermarkets were set to have free charging at 7kW. The intention in this research was to capture real-world trends; there are some partnerships between retailers and car manufacturers to provide free charging at supermarkets: Tesco is working with Volkswagen to provide free charging at 7kW at 600 stores by 2020 (BBC, 2018). The charging characteristics of land use for office, shops, and school/college were also set as free at 7kW, to account for other potential free sources of charging, and to represent the variety of options for charging.

Table 5-2 Charging rates by parking type and landuse

PARKING TYPE	LAND USE	CHARGING RATES
On-street metered, off-street station car park	All	£0.6139/kWh at 22kW
On-street resident scheme & miscellaneous parking	All	£0.2139/kWh at 22kW
Off-street private non-residential parking, off-street shop carpark	Supermarkets, offices, shops, school/college	Free at 7kW
Off-street private residential		Varies H2V not enabled: £0.4139/kWh at 22kW H2V enabled: dependent on residential energy pricing if
On-street other, off-street public other, and all others	Others	£0.4139/kWh at 22kW

5.1.3 Residential energy demand

Temporal residential energy demand data was required for the optimization. Energy demand profile data was required to allow the optimization to harness opportune times of low and high demand for synergetic energy management. Using a real data source would capture a realistic scenario. It is important to recall the important findings of this research. The important findings include analysis of the added value of a DST, the extent of benefits for individual users, potential differential distribution of the benefits across society and the effects of different components of the integrated energy system. Therefore, as important as having the energy demand profile is, there is greater importance on using the profile than there is on the exact accuracy of the profile. The DST would be able to add value for as long as there was a profile for the user to optimize. The findings of the effects of the other elements of the system are key. The profile used in the research can be seen on Figure 5.3.

The average hourly electricity load profile of residential households was taken from the Household Electricity Survey: A study of domestic electrical product usage (GOV.UK, 2013). This survey was used in a previous study analysing home energy system with PV, BESS, and EV charging (Chitsuphaphan, Yang and Dai, 2020). Residential energy demand was assumed to be constant within the respective hour. The report used a sample of 251 households in the UK to generate national average daily load curve for different types of households, different days (weekday, weekend, holidays), and for

households with or without the presence of electric heating. The sample of households that were recruited for the survey had a similar distribution of different demographics, such as social grade, household size, with the average in England. The report details the comparison of the distribution of the different demographics of the sample with that of England.

The profile selected for use in this research is the profile across all house types, across all days, and for houses without electric heating. The profile for households without electric heating was chosen as 77% of UK households use gas heater as the main method of heating (Statista, 2021a). Each minute within the hour was set a demand, to fit the time resolution used in the optimization.

The data was for the UK. Therefore, it had to be adjusted to fit the case study based on London. A London adjustment factor was calculated by dividing the London average total household energy consumption by the national average. This factor was multiplied to the national average household demand profile. The residential demand profile for London households was assumed to be the same as the national average household demand profile. The London average residential energy consumption data was taken from the Electricity Consumption by Borough dataset from the Department for Business, Energy & Industrial Strategy (LondonDatastore, 2018). The average consumption per meter in each borough of the London was multiplied by the number of meters in that borough. The consumption was summed across all boroughs, then divided by the total number of meters in London to calculate the London average. The household demand profiles were assumed to be the same for all households. The household demand was assumed to be the same for households of the same size. The UK average annual consumption was very similar to that of London; 3,567kWh in the UK, and 3,589kWh in London.

To account for households of different sizes and the effects of household size on residential energy demand, the residential energy demands were factored by weightings based on household size.

Weighting of energy consumption for household size was taken from the National Energy Efficiency Data-Framework (NEED) consumption data tables by the Department for Business, Energy & Industrial Strategy (Department for Business and Strategy, 2020). The average electricity consumption by number of bedrooms was taken as proxy for number of residents. The average electricity consumption by number of bedrooms was used to weight the overall household demand by household size from the input data. The average electricity consumption by number of bedrooms was assumed to be the same as for number of residents. In obtaining the average profile, the survey used a share of household sizes that was very similar to the UK's share of household sizes at the time. That is, the average number of occupants in a household used in the survey was very similar to that of the UK. Therefore, weighting the consumption by household size is appropriately performed, as the initial

average household size in the original profile is similar to that of the UK. The UK average household size from the 2011 Census was 2.3 (Status *et al.*, 2012).

The weightings for residential energy demand by household size was interpolated for the London average household size of 2.47 from the 2011 Census (Status *et al.*, 2012) to give the weighting to residential energy demand for the average London household size. This adjusted profile for London can be seen in Figure 5.3. The household consumption factored for London was then divided by this interpolated weighting for the London average household size, to give the demand profile per 1 person.

This data was then used in the optimization where the average per person London household energy consumption was multiplied by the respective household size residential energy weighting, based on the household size as reported for each individual in the LTDS.

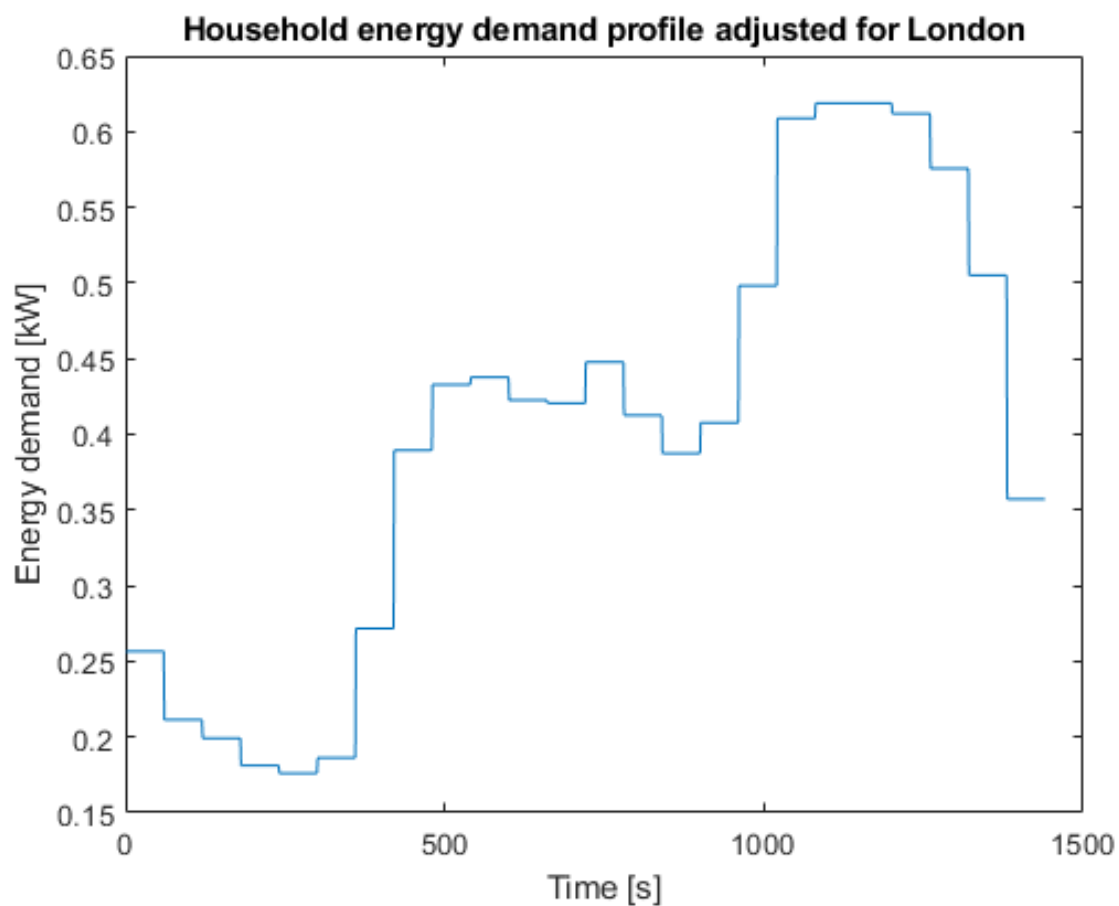


Figure 5.3 London household energy demand profile.

5.1.4 Residential electricity tariffs

To study the effects of different tariffs on the financial benefits of BEV users, data for residential tariffs were needed. Specifically, prices of electricity for temporally fixed (flat/same price at all times of the day), and temporally varying were needed. In this research, the type of temporally varying tariff to be tested was specifically tariffs that varied for every half hour. This type of tariff is referred to as dynamic Time-of-Use tariff.

The fixed-rate, flat price tariff was based on average London electricity price; this is the most common tariff. A fixed-rate tariff has been used in previous studies (Alirezai, Noori and Tatari, 2016; Payne and Cox, 2019). The flat price residential energy price was taken from the UK's Department for Business, Energy & Industrial Strategy using their annual domestic energy bill statistical data set for the 2018 values. The price of electricity for the model was set as the average domestic variable price of £0.155/kWh (GOV.UK, 2019). The fixed charge of £0.2435 per day was not included, as this charge would be paid by the user regardless of having a BEV and does not affect the optimization. However, it is acknowledged that that does form a part of the overall electricity cost of an individual, with an average value of £88.88 per year in London.

A high-resolution, half-hourly dynamic TOU residential energy tariff profile was required to analyse the effects of such a tariff on the financial benefits gained from optimized BEV-home energy management. Real-time TOU residential energy tariff was used in a few previous studies (Abdelaal *et al.*, 2021; Taik and Kiss, 2021). As discussed in Subsection 4.3.5, many studies referred to the usage of TOU, but many had only a few (2-5) price points across a day. The dynamic TOU tariff residential energy data used in this thesis were based on the half-hourly pricing given by Octopus, an energy provider in the UK, which is one of the most innovative providers in providing a varying tariff. The data were pre-processed to obtain a value for each minute of the day to fit the time resolution of the model. The value in the dataset at each half hour interval was applied to the following 29 minutes, giving each minute within the half hour intervals the same price. Three pricing scenarios of half hourly tariffs were used (low, average, and high). To obtain the average price scenario, the half hourly prices from beginning of 2018 to May 2019 (the full data) was averaged. For example, all the prices at 9:30am over the length of the data was averaged to give the average price at 9:30am. The average price scenario had an average price of £0.135/kWh. The high and low scenarios used were based on the two months which had the highest and lowest monthly overall average prices, September 2018 (£0.154/kWh) and May 2019 (£0.120/kWh) respectively. The price at each half hour during September 2018 and May 2019 respectively were averaged, to give the price for the higher and low scenarios. The reason these two months were used was because the prices varied month to month, and year to year. There were

no clear seasonal peaks which could be used. Therefore, the months of highest and lowest prices were used.

Using this dataset allowed the research to analyse and give findings of a potentially more common future scenario, made possible by the increasing smart meter installations. The research achieves this by analysing an integrated energy system of individual BEVs, residential energy demand, PV, BESS and V2H2G, with half-hourly electricity prices.

A three-rate tariff offered by Green Energy in the UK was also found during the research, where the day is split into 4 segments, with 2 of the segments having the same price, and the other 2 having 2 different prices (Table 5-1). It was pointed out to be the only 3-rate TOU tariff available to domestic customers in the UK, and predicted to become more popular and common as smart meters are installed (Küfeoğlu, Melchiorre and Kotilainen, 2019).

Table 5-3 Three-rate tariff offered by Green Energy

Time (hr)	Weekday price (£/kWh)	Weekend price (£/kWh)
0-7am	0.0641	0.061
7am-4pm	0.1402	0.1402
4pm-8pm	0.2999	0.1402
8pm-12pm	0.1402	0.1402

Given the trend of moving from flat price to real-time prices, and the impending installation of smart meters allowing for higher time resolution, it was thought relevant and important to analyse the half-hour scenario, more so than the three-rate tariff scenario.

5.1.5 H2G & V2G income prices

High-resolution temporal V2G and H2G price profiles were required to study the effects of real-time H2G and V2G pricing on financial benefits of individuals. The H2G pricing data was obtained from a released sample data of half-hourly export rates provided by Octopus from 1st of January to 31st December 2018 (Octopus, 2019) and averaged across the year, for London only. Similar to the residential dynamic TOU tariff, the half-hourly prices were allocated for each minute time resolution in the optimization.

Of the companies currently offering small export guarantee (SEG) in the UK, Octopus and Bulb measures the export with a smart meter. Octopus has a half-hourly variable export tariff available to

consumers under Agile Outgoing Octopus with the export payment based on day-ahead wholesale price (Octopus, 2019). Octopus also offers a fixed plan of 5.5p/kWh (£0.0055/kWh). The variable pricing was chosen as it allows the desired analysis of effects of temporal variation.

Three H2G pricing scenarios were used in the model: average, low and high. They had average prices of £0.0712/kWh, £0.0617/kWh, and £0.0832/kWh respectively. For the average price scenario, the half hourly price was averaged from the beginning of 2018 to May 2019 (the full data). The average was taken as the prices varied month to month, and year to year, with different prices in the first half of 2019 compared to first half of 2018. For the high and low-price scenarios, the prices were based on the two months which had the highest and lowest monthly overall average prices, September 2018, and May 2019 respectively.

These pricing scenarios allowed the analysis of impact of variances in price of H2G income on the benefits to individuals having access to an optimization tool. Figure 5.4 shows the plot of all half hourly H2G prices in the data set. The average prices represent the characteristic pattern present in the pricing variation throughout the day observed across all months. The highest and lowest average months provide a good envelope of upper and lower levels. It is acknowledged that September 2018 does not reach as high of a peak during the peak hours, however, it was selected as it does capture the most ubiquitously high prices through the day.

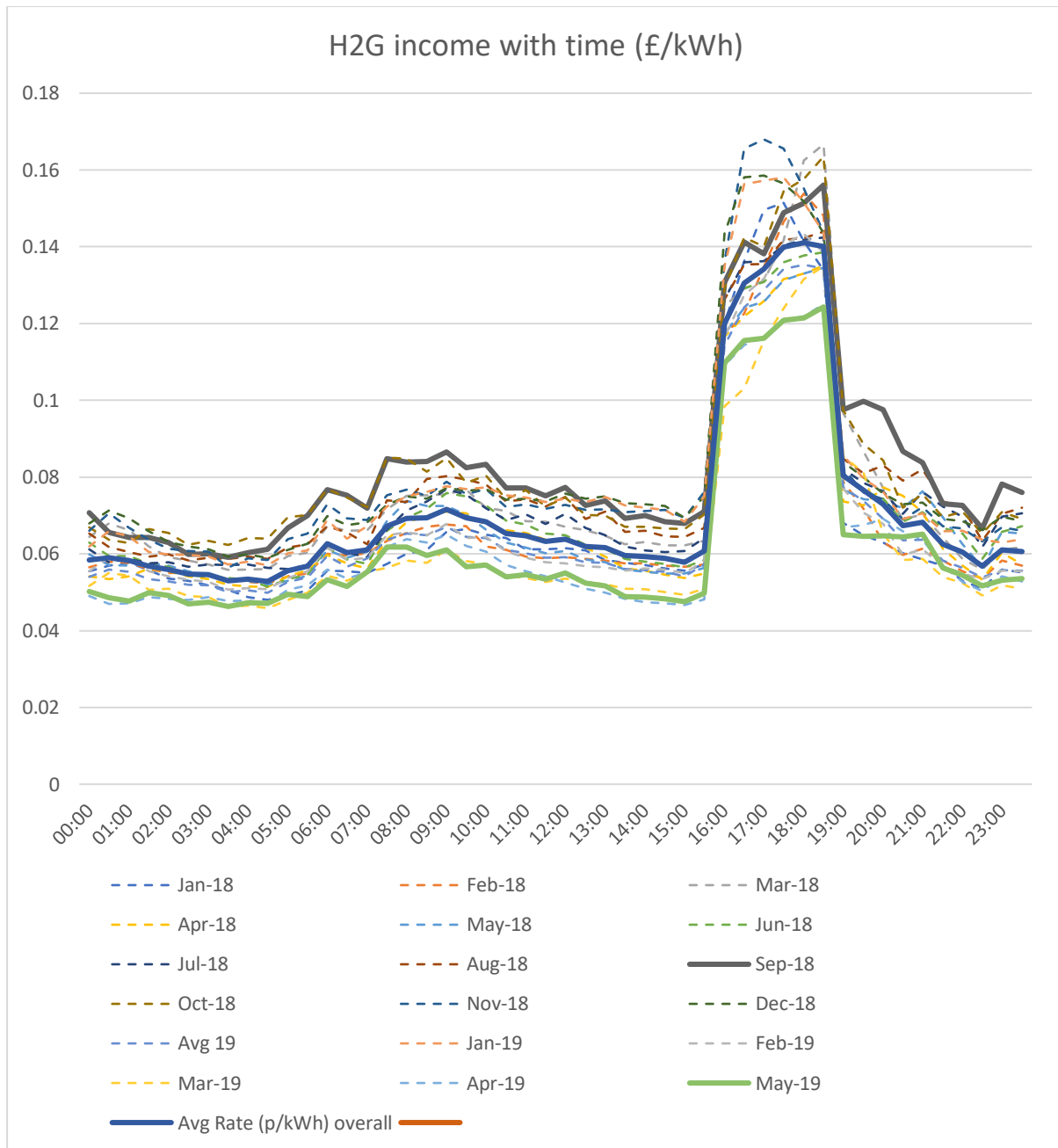


Figure 5.4 H2G income with time £/kWh.

The H2G pricing was assumed to be the same for all households.

The V2G pricing was assumed to be the same as H2G pricing on the basis that the H2G pricing collected was the price based on export wholesale market, and therefore represents willingness of the grid to purchase energy. This value to the grid was assumed to be the same regardless of whether the source was from H2G or V2G. The pricing available was for retail customers, and represents a real price available to individual users, as opposed wholesale prices which may be only available to building operators, or aggregators; a similar proposition was made by Payne and Cox (2019).

5.1.6 PV generation

A high-resolution temporal PV generation profile was required for the optimization. Hourly PV generation data for London was obtained from photovoltaic geographical information system (PVGIS) climate monitoring satellite application facility (CMSAF) (European Commission, 2017a). The hourly dataset contained PV generation values at every 55th minute of each hour, for every day from 1st of January 2007 to 31st of December 2016. PVGIS was used as the source for PV generation data in previous studies using one year's worth of data (Lazzeroni *et al.*, 2019; Scorrano *et al.*, 2020). It is a reliable source of PV generation data. The calculated results were reported by PVGIS as having been validated against ground measurement stations (European Commission, 2021b), and most were within 5% (European Commission, 2021a).

The PV generation data was obtained at the coordinates of latitude 51.501 and longitude -0.125, which is the location of Big Ben in central London. The data for 1kWp crystalline silicon PV technology was extracted, then later factored depending on the scenario parameter PV generation output. Slope inclination and azimuth for the PV panels were optimized by PVGIS CMSAF for the highest energy output for the whole year for fixed mounted PVs (slope 39 deg., azimuth -8 deg. where south is 0 deg.). This is similar value to the value of 30 degrees slope facing south used in a study for their data for PV generation in Westminster (Munkhammar *et al.*, 2015). It was noted that PV power output for tilt angles between 20 and 50 degrees is negligible within a few percent production difference (Mondol, Yohanis and Norton, 2007). Thus, the setup from PVGIS CMSAF was used. The values calculated for PV generation accounts for the temperature dependence of the performance. Effects of clouds are also accounted for as PVGIS uses solar radiation data based on satellite images which are used to identify the presence and the thickness of clouds.

Meteonorm, which was used in a previous study (Munkhammar *et al.*, 2015), was also be considered however, the output format of PVGIS was preferred.

To analyse the effects of different PV generation output on the extent of financial benefits for individuals, two PV generation scenarios were tested: winter and summer scenarios. The seasons affect not only the overall amount of energy produced each day, which could be tested by setting different overall daily PV generation, but also affects times at which energy is generated, and thus the time availability of off-grid energy for EV charging or for storage. For example, in the summer with earlier sunrise, energy could be stored in the EV or BESS prior to residential or EV energy demand occurs, as the users may awake after sunrise. The analysis of impact of time of generation is possible as minute resolution PV generation data is used, as opposed to a daily overall.

To obtain the two scenarios, average hourly values for winter (December) and summer (June) were obtained by averaging the values at each hour for each day in December and June respectively for all the years in the dataset. December and June were chosen as these months have the lowest and highest PV generations respectively at 8.32W and 35.3W respectively. It did not make sense to take an average value across the year, as, generally, such a day would not exist in reality. That is, there is no day in the year, normally, where there is an early sunrise, with lower radiation, which would result from averaging sunlight at, for example, 6am, of winter months (0) with summer months (non-zero).

Some assumptions to the data were made. PV generation was assumed constant for all the household locations in the LTDS for each given scenario of PV size parameter. Solar variability correlation for PV production for regions within the size of Westminster is nearly 1 (Widén, 2011; Munkhammar *et al.*, 2015), and this research took the assumption that the PV generation is constant within London, albeit London being a larger area than Westminster.

This research intended to analyse the benefits to an individual who may have access to a certain amount of PV generation, or to advise whether an investment could be beneficial. Values such as average available rooftop area was not used as a parameter for PV generation in this research. Instead, the question to be answered was what benefits an individual may gain from having PV, and how it is affected by the PV size. This allows individuals, or policies, to be informed on potential benefits of specific sizes, and worthiness of investing.

5.2 Additional scenario parameters and additional model settings

The additional scenario parameters and additional model settings selected for the model are detailed in this section. Some of the scenario parameter data were outlined in the previous section. Those scenario parameter data were:

- Residential energy pricing
- H2G and V2G income prices
- PV generation

The additional scenario parameters are:

- BEV model specifications
- PV panel size
- BESS capacities

The additional model settings are:

- Minimum state of energy
- Minimum duration of stay for charging events
- Charging rates
- Grid power rating
- Capital cost

5.2.1 BEV model specifications

The specifications of BEVs used in the optimization are detailed here. The BEV model specifications tested were based on real BEV models to test for real specifications that exist and are realistic. However, the analysis of the effects of the BEV specifications could be generalised and be applicable to other BEVs and their specifications.

The BEV specifications used in the model were that of the Nissan Leaf, Hyundai IONIQ, MG ZS and Tesla Model Y. The specifications are shown on Table 5-4.

Nissan Leaf was selected as the primary model to base the optimization around, as it is a common model. The highest newly registered BEVs in the UK in 2018 were Nissan Leaf (5,300), Renault Zoe (2,000), Tesla Model S (1,900), Tesla Model X (1,500) and BMW i3 (1,200) (Department for Transport, 2019). Nissan Leaf has been used in previous studies (González *et al.*, 2014; Alirezaei, Noori and Tatari, 2016).

To compare the impacts of different BEV specifications, the Hyundai IONIQ and MG ZS were also tested. These enabled a parametric study for the different specifications of BEVs. The Hyundai IONIQ was selected as it has a similar battery capacity as the Nissan Leaf, but longer range. It allowed analysis of impacts of mileage from charging, whilst holding the storage potential of BEVs and their potential role as energy carriers constant. To analyse effects of the storage potential of BEVs, the MG ZS specifications were tested. The MG ZS has a similar range, but a larger battery capacity. Finally, to consider the effects of a higher specification model the Tesla Model Y specifications were used. The specifications used were as reported by the World Harmonized Light-Duty Vehicles Test Procedure (WLTP) (Electric Vehicle Database, no date).

Table 5-4 BEV specifications

MODEL	BATTERY CAPACITY [KWH]	RANGE [KM]	FUEL ECONOMY [KM/KWH]
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NISSAN LEAF	40	270	6.75
HYUNDAI IONIQ	38.3	310	8.09
MG ZS	44.5	262	5.89
TESLA MODEL Y	75	540	7.2

Another important BEV specification is the charging and discharging efficiency of BEV batteries. These were taken as 95%, and a round trip efficiency of 90%. These values were used in previous work (Valøen and Shoesmith, 2007; Gao *et al.*, 2011; Mao *et al.*, 2018; Ruiz and Persio, 2018; Chitsuphaphan, Yang and Dai, 2020; Wang *et al.*, 2020; Duman *et al.*, 2021).

5.2.2 Minimum state of energy

A minimum SoE for BEVs were set in the model to provide a buffer and represent the risk adverse nature of users to use their battery to practically empty. The minimum SoE was set as 10%. The minimum SoE was applied in the optimization by decreasing the stated BEV battery capacity by 10%. This similar to how ICEV reserve fuel tanks work, where there is no actual reserve tank, and the empty tank light comes on when the fuel level reaches the reserve level. ICEV reserve fuel tank typically vary between 10-15% of tank capacity (RAC, 2019).

The approach of decreasing the stated capacity was chosen over having a minimum SoE of 10% within the optimization as this would have made necessary a starting SoE of 10%, implying BEV users needed to be given free energy at the start of the optimization. There were implications to BEVs starting with a pre-charged minimum SoE. The results would have been unrealistic for cases where the minimum SoE was similar to the mileage, or the extreme case where that minimum was enough to cover a whole day's journey, meaning they would travel for free without charging. However, the impacts may be negligible if the total mileage driven was relatively larger than the range of the BEV.

5.2.3 Minimum duration of stay for charging events

A minimum duration of stay during which charging events were allowed to take place was desired to be set to capture the realism of not charging when the DoS is too short. For example, a BEV user staying at a destination for 1 minute is very unlikely to charge.

A report compiling results from various surveys found that the average maximum amount of time consumer drivers would be willing to wait in order to charge in-transit is just 13 minutes (PwC

Strategy&, 2019). This could mean that EV users would be willing to charge for even short amounts of time, of 13 minutes or less, if required.

The minimum duration of stay for charging events to take place was selected as 5 minutes. Therefore, any duration of stay which was less than 5 minutes would not allow charging in the optimization model. This was justified given the short amount of time taken to plug in an EV for a charging session in most cases depending on time it takes to verify the charging session from the service provider. There may be a lack of reason in plugging in to charge for only a few minutes, unless critical, however, given that with a charger of rating of 22kW or 50kW, 1 minute of charge can charge several km of range, it is the author's opinion that restricting charging for short stays (5-10 minutes) is not necessary.

5.2.4 Charging rates

Charging power rates for different locations were set at different rates.

The charging rate at private homes was set at 7kW. 3kW, 7kW, 11kW and 22kW ratings are all available, and 7kW was representative of the available rates. A survey from the Canadian Plug-in Electric Vehicle Study reported home charging power rates by respondents as either 1.9kW or 9.6kW (Wolinetz *et al.*, 2018). 7kW captures the range of available home charging infrastructure providers in the UK such as podpoint 3.6kW, 7kW, 22kW) eo (3.6kW, 7kW, 11kW, 22kW) wallbox (7.6kW and up to 22kW).

All charging rates in public were set as either 7kW or 22kW. 7kW was set for locations of free charging, such as supermarkets. 22kW was set for locations of paid charging. The authors acknowledge that this is an approximation and a generalisation, and not accounting for choice of different charging rates available at different prices. Whilst there are many 3kW chargers available in London, generally the price per kWh is cheaper for 7kW or 22kW chargers than for 3kW, thus, it was assumed that the choice of 7kW or 22kW charging would be preferred. It was assumed that there were always 7kW or 22kW chargers available at charging points. It also captured a middle ground of currently available 3kW, 7kW, 22kW and 50kW chargers. The rate of 7kW was widely available in public, and used in other studies (Zethmayr and Kolata, 2019). Faster public charging rates, such as 22kW, 50kW and 150kW are becoming more common, and would be of interest in future studies.

5.2.5 Grid power rating

The maximum power rating between the house and grid was set at 20kW. In previous work, 24 kW connection capacity per household was used (Salpakari *et al.*, 2017), which corresponded to three-phase power with 35-A main fuses and a phase voltage of 230V; in that study, the maximum power

capacity of the connection between the microgrid consisting of 1-10 households and the utility grid was scaled based on the number of households in the microgrid. 16.5kW was used in a previous study (Doroudchi *et al.*, 2018) as the capacity of power between building and grid. The details of maximum power to the grid from the house was not present in some previous studies (Munkhammar *et al.*, 2015; Alirezaei, Noori and Tatari, 2016).

5.2.6 PV panel size

Appropriate PV panel size and outputs were required to test the effects of different PV generation on the financial benefits for individuals. PV outputs at peak of 0.3kW, 1kW, 3kW, and 9kW were selected for the optimization and analysis. At 20% efficiency, these equate to PV panel sizes of 1.5m², 5 m², 15m² and 45m². Whilst 45m² is a very large PV configuration, 40m² was seen in previous work (Doroudchi *et al.*, 2018). 20% PV system efficiency was selected, which gives the conversation between kW and area of the panels as listed above. 150 W/m² Peak power is reasonable for a typical Silicon-based PV module with 15% efficiency (U.S. Department of Energy, 2012), and given increase in efficiency in PV technology, 20% was selected. System losses was set as 14% as default on PVGIS, from causes such as losses in cables, power inverters, dirt/snow cover.

The sizes selected represent the range of sizes available to individual homeowners in the UK, and outputs seen in previous studies. Average PV capacity per household in London is estimated to be around 3.3kW (Greater London Authority, 2018). The cumulative confirmed Feed-In Tariff installations of domestic PV in London as of 1st quarter of 2019 were 23,890 out of 3.77 million households, with a total capacity of 78,937kW, and an average of 3.3kW (GOV.UK, 2019). The GLA estimated that approximately 50% of London's roofs could be suitable for PV (London Assembly, 2015). A study estimated that in Westminster, London, the maximum available PV area per household was 1.53m² considering domestic rooftops only, and 4.4m² for all potentially reasonable available rooftop area (Munkhammar *et al.*, 2015). A study assessing distributed solar PV across Great Britain found future median domestic PV installation size for cities to be 3.1kW (Few *et al.*, 2020). A study in Northern England used average daily solar power of 0.642 kW (Strielkowski, Štreimikienė and Bilan, 2017). Another study of the role of PV-BESS system in the UK used 2kW household PV capacity (Dong *et al.*, 2018). A study for the urban setting of Kyoto and Shenzhen used PV capacities ranging from 0 to 10kW (Kobashi *et al.*, 2020). A study for a single-family residential building in Poland used a 4.48kWp PV system (Cieslik *et al.*, 2021).

It was opined that PV of 1m²-5m² was marginal for household scenarios (Munkhammar *et al.*, 2015), and instead a 30m² per household PV area was adopted for a study of the City of Westminster borough,

London, which was stated to correspond to an annual net-zero energy consumption for a 2 resident apartment. The caveat was stated in the study that the 30m² per household PV is only possible when “most of Westminster is not covered in PV modules”. It would be interesting to analyse the effects of magnitude of PV generation on its benefits to EV users through parametric analysis.

5.2.7 BESS capacities and power ratings

Different BESS capacities were used as parameters in the optimization. A broad range of 5kWh, 10kWh, 15kWh and 45kWh were used for the optimization and analysis. These capacities, apart from the 45kWh, are available for consumers in the UK. Powervault offer batteries of capacities 4.1kWh, 8.2kWh, 12.3kWh, 16.4kWh and 20.5kWh. Many other manufacturers such as LG and Tesla also offer battery capacities in a similar range. A study for the urban setting of Kyoto and Shenzhen used BESS capacities ranging from 0 to 20kWh (Kobashi *et al.*, 2020). A study focused in India for a residential integrated energy system used a 10kWh BESS in its system make up (Muthiah-Nakarajan *et al.*, 2021).

Power rating and efficiency of the charging and discharging of BESS are other important specifications. The power ratings were set as 3.3 kW for the input, and 5.5kW for the output, which are the specifications for the Powervault BESS (Powervault, no date). The efficiency of BESS was set at 95%. This reflects the 90% roundtrip efficiency that Tesla Powerwall has (Tesla, 2020). 95% efficiency was used in previous studies (Chitsuphaphan, Yang and Dai, 2020; Wang *et al.*, 2020; Duman *et al.*, 2021). Interestingly, a very high efficiency of 99% was seen in previous work (Wu and Sioshansi, 2017).

5.3 Uncertainty in data

It was recognised that the data was not perfect and there were uncertainties in the data. Uncertainties could impact the results, and their reliability. Some uncertainties in the data could not actively be controlled for. The possible uncertainties in the data could be from the travel pattern data (LTDS), PV generation/solar irradiance (CMSAF), residential energy demand, residential energy pricing, and H2G and V2G pricing.

To mitigate the impact of data uncertainty on the results, sensitivity analysis was carried out on residential energy pricing, and H2G and V2G pricing. This is detailed further in Section 6.5.

Chapter 6

Evaluation of results

This chapter presents the results of the optimization, and their analyses, achieving RO2. The methodology used in the analysis is detailed in Section 6.1. Section 6.2 presents the results and discussion with subsections addressing each formulation. Within each formulation subsection, the RQs and Hyps being addressed are discussed. The model estimation results are presented and interpreted from the parameter estimates and t-statistics for the explanatory variables from multivariate linear regression. The validation of the results is detailed in Subsection 6.4. Subsection 6.5 details the sensitivity analysis. Subsection 6.6 provides a summary of the results. This chapter contributes to accomplishing RO2.

This research had the aim of providing meaningful insights through the results and analyses presented in this chapter on the extent of benefits and their distribution for individual BEV users of optimizing their BEV operations integrated with their residential energy demand, PV, BESS, and V2H2G. Furthermore, it was aimed to inform on potential implications to other stakeholders in BEV adoption and the transitions in the energy system. This was from the perspective of how much individual users could gain financially, depending on the technology configuration they might adopt from the various combinations of PV, BESS, and others. This perspective was taken, rather than analysing the effects of widespread adoption of certain technologies across a sample population. This would then allow analysis of the distribution of benefits of individuals across demographics.

The results and analysis presented in this chapter are from the optimization problem solved for the London case study using LTDS data. Each scenario solved consisted of 3,260 individuals' travel itineraries. Overall, across the three formulations, there were 1,477 scenarios. This yielded in 4,815,020 results of individuals' benefits overall. To draw meaningful insights from the large number of results, an evaluation of the impacts of the BEV user travel pattern characteristics, BEV user characteristics and scenario parameters on the results was conducted using regression analysis. Performance Metrics (PMs) were selected to enable comparison between the results.

6.1 Analysis methodology

This section outlines the methodology for analysis of the results, which is visually outlined in Figure 6.1. The results of the optimization were used to understand the relationships of extent of financial benefits with user characteristics and energy system setup. Multivariate linear regression was used to perform the analysis. The analysis taken were:

- to analyse the effects of different travel characteristics
- to analyse the distribution of benefits segmented across the demographic characteristics

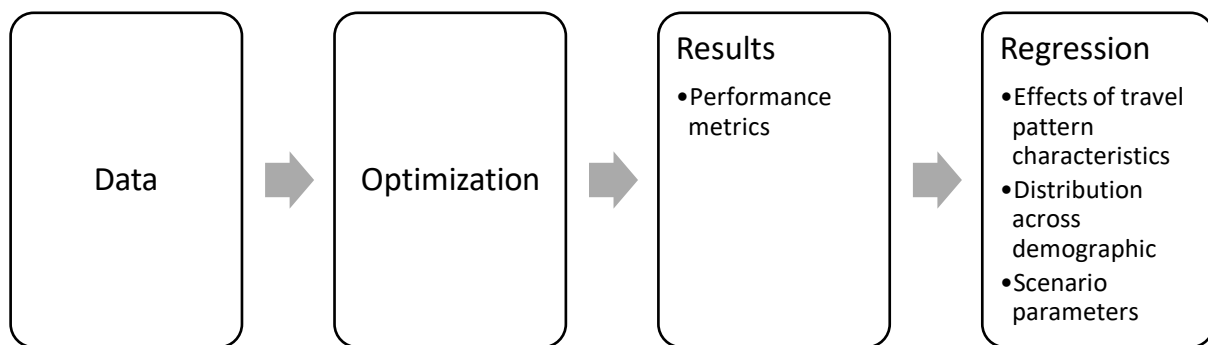


Figure 6.1 Process of analysis

The analysis methodology is outlined by first discussing the choice of variables, followed by the performance metrics used to represent the extent of benefits gained by users.

6.1.1 Performance metrics

The optimization solved the problem formulation to give the results. The results for the optimized cost were used as the performance metrics. The performance metrics used for the extent of financial benefits are described in this section. Two performance metrics are used: financial benefit, and financial benefit %. Note that in the analysis, the financial benefit was the main performance metric used, and the regression models were made around the financial benefit. In some cases, the financial benefit % is also analysed to add context, and in those cases, the same model for the financial benefit with the same categories was used to enable comparable analysis. It is acknowledged that a model based on the financial benefit % as the response may have different categories which are more appropriate.

Financial benefit is the gain in £ from optimized charging scheduling and energy management compared to the baseline cost on a per travel itinerary day basis (Equation 2). The per day basis allows fair comparison between scenarios of different optimization horizon lengths. In cases where the user is paid from selling to the grid, the optimized cost was negative, giving a higher positive value of benefit.

$$\text{Financial benefit} = \frac{\text{baseline cost} - \text{optimized cost}}{\text{number of days}} \quad [2]$$

Financial benefit % (Equation 3) represents the financial benefit as a percentage of the baseline cost and is the reduction in cost with respect to the baseline cost. A 75% financial benefit means the optimized cost was a quarter of the baseline cost, and hence a 75% reduction in cost. Where the user has an overall income for the operations, their optimized cost would be negative, leading to benefits of over 100%. For example, where a user has an income equal to their baseline cost, they would have 200% financial benefit percent, i.e., reducing their cost by double their baseline cost.

$$\text{Financial benefit \%} = \frac{\text{financial benefit}}{\text{baseline cost}} \quad [3]$$

The optimized cost was calculated with the total electricity cost minus the cost of the residential electricity demand if it had been met solely through the residential energy service provider at their price (Equation 4; terms defined in Section 4.1). This residential electricity cost was calculated simply as the residential energy demand profile multiplied by the electricity price at the respective time of day matching the energy demand profile. The reason for the subtraction of the residential cost is that the solution to the optimization gives the optimal cost considering all import and export costs of energy. The adjustment to subtract the cost of the residential electricity demand was made as this gave a true value added of the integration of a BEV and the wider energy system context, and financial benefits possible from it. It allowed comparison with the baseline scenario on even terms, with neither considering the household energy cost. The baseline cost only includes the cost to charge the BEV to meet its travel itinerary, in a dumb charging manner, and does not include any household energy demand.

$$\begin{aligned} \text{Optimized cost} &= \text{Total cost of energy bought from the grid} \\ &\quad - \text{cost of residential energy demand} \\ fval_{adj} &= \sum QC - \sum GR + \sum GSB - \sum SGI - \sum HB \end{aligned} \quad [4]$$

It was decided to subtract the household electricity from the integrated system, rather than add on the cost to the baseline EV charging cost. The latter would have made the overall values larger and

mask the true contribution of the optimization by adding on a constant cost, which is not affected by the BEV operations. Furthermore, it was of interest to address the research question of analysing the extent of benefits of a DST, beyond just charging decisions, and include decisions for BESS control. This approach allowed analysis of how a DST can improve charging and energy management cost for residential energy by harnessing the synergy of BESS and real-time dynamic TOU energy prices. For example, even if the BEV did not travel at all, it would be optimal to pre-charge the BEV and BESS at times of lower residential energy cost and meet the residential energy demand with it at times of greater cost. The adjusted solution to the optimization allows this analysis. Note that the value can be negative, meaning the user has a net income.

6.1.2 Regression

To analyse the results for effects of travel pattern characteristics and distribution across demographic, multivariate linear regression analysis was conducted. The significance level was set at $p < 0.05$. For statistical analysis, MATLAB 2020a was used with Statistics and Machine Learning Toolbox. Linear regression was used to provide initial insights on the differential distribution of financial benefits across demographics, and the effects of the various travel pattern characteristics and different available technologies. It is acknowledged that linear regression assumes normal distribution of the benefits. Thus, a generalised linear model would yield better insights, and would be an important future work.

6.1.2.1 Variables

The variables chosen to analyse the extent of financial benefits are outlined in this section. There were three groups of variables used. They were chosen as they enabled answering the RQ1, RQ2, and RQ2 (Section 2.4).

- Travel pattern characteristic: to understand the effects of individual drivers' travel patterns on extent of benefits.
- Demographics: to understand the distribution of benefits across specific segments of the population by income, ethnicity, and employment status.
- Scenario parameter: variables changed across scenarios to understand their effects on the extent of financial benefits e.g., BESS capacity.

All the variables used in the regression are outline in Table 6-1, and further explained in the following subsections. Categorical variables were used, including for variables which were originally continuous, such as driving distance. This was done to better capture the variations of relationships between

benefits and variables. They gave more insights to the non-linearity within the results. They also allowed grouping the travel pattern characteristics into profiles of users.

Table 6-1 All variables used in regression.

Travel pattern characteristics	Demographic	Scenario parameters			Others
Total driving distance	Income	Number of days	H2V	BESS capacity	Access to and usage of private off-street parking
Number of stays	Ethnicity	BEV model	V2H	PV capacity	Household size
Average duration of stay	Employment status	Residential energy price	H2G	PV season	
		H2G price	V2G		

6.1.2.1.1 Travel pattern characteristic variables

The user travel pattern characteristics were used as regression variables to understand the effects of travel pattern characteristics on the extent of benefits for individual BEV users. The analysis gave insights to which technology setups would be the most beneficial for different profiles of users. This could allow more concentrated, effective, and tailored adoption of technologies, through informing the right choice of policies for governments, and business strategies for businesses such as BEV sellers, energy providers, and CSPs.

The travel pattern characteristics used were:

- Total driving distance
- Number of stays
- Average non-overnight DoS

Each variable was taken for one day's travel itinerary. In analyses involving multiple day horizon, the variables were also for one day's travel itinerary. Using a per day basis allowed like for like comparison across travel pattern characteristics. That is, an individual who travelled 10km on day one, and 10km on day two, had their travel distance variable as 10km. Similarly, the benefits were also calculated on a per day basis (further explained in 6.1.1).

These variables were selected out of many other travel pattern characteristics available from the LTDS (Table 6-2; the 3 selected variables are underlined and italicised). The selection of the variables used was based on the correlation (Figure 6.2; the selected variable correlations are circled in red, and the others are crossed in yellow) and collinearity (Figure 6.3) between them, using Pearson correlation coefficient and Belsley collinearity diagnostics respectively. The above three variables were chosen as they had low correlation between them and captured the types of characteristics that define travel pattern characteristics and shows insight to the difficulty of charging a BEV. It was hypothesised that decision making with the many variations in charging prices and rates and considering the adequate SOE for each trip would make the operating cost non-optimal. Therefore, the difficulty of charging decisions leading to non-optimal charging scheduling would be due to:

- Number of instances of decision making (represented by number of stays)
- Availability and time pressure of charging instances (represented by total duration of stay)
- The degree of impact (represented by total driving distance) of those decisions

Table 6-2 Predictors of difficulty of decision making and reasons for choice. The 3 selected variables are underlined and italicised.

Indicator	Description	Reason for use
<u>Number of stays</u>	<u>Number of stays of an individual's day's travel itinerary</u>	<u>A proxy for the number of instances of decision making.</u>
Number of trips	Number of trips of an individual's day's travel itinerary	A proxy for the number of instances of decision making.
Number of stays and trips	Number of stays and trips of an individual's day's travel itinerary	A proxy for the number of instances of decision making.
Average DoS	Average length of all the DoSs in an individual's day's travel itinerary	Is the amount of energy chargeable in a stay, the amount of time to make each decision, and for time for flexibility in charging decision making. It represents the effect of a decision on the optimality of the decision made.

Average DoT	Average length of all the durations of trips in an individual's day's travel itinerary	Represents a combination the amount of energy needed for each trip and the amount of time not available to charge. A proxy for the pressure on each decision instance.
<u>Total DoS</u>	<u>Total length of all the DoS in an individual's day's travel itinerary</u>	<u>Is the total amount of energy chargeable across all stays, the amount of time to make all decisions, and for time for flexibility in charging decision making. It represents the effect of all decisions on the optimality of the decision made.</u>
Total DoT	Total length of all the DoT in an individual's day's travel itinerary	Represents a combination the amount of energy needed for all the trips and the amount of time not available to charge. A proxy for the pressure for all decisions.
Average trip distance	Average distance of trips in an individual's day's travel itinerary	Represents the amount of energy needed on average for each trip, and therefore the immediate minimum amount of energy needed. A proxy for the impact at each decision instance.
<u>Total distance</u>	<u>Total trip distance in an individual's day's travel itinerary</u>	<u>Represents the total energy needed, and thus the overall need that the charging decisions must fulfil, and impact of decisions made on the operating cost</u>
Average non-overnight DoS	Average length of all the non-overnight DoSs in an individual's 1-day travel itinerary	The average DoS of the stays excluding the overnight DoS. Represents how much time/flexibility there is to make decisions at each decision instance, excluding the decision instance over the lengthy overnight stay.
Total non-overnight DoS	Total length of all the non-overnight DoSs in an individual's day's travel itinerary	The total DoS of the stays excluding the overnight DoS. Represents how much time/flexibility there is to make decisions across all decision instances, excluding the decision instance over the lengthy overnight stay.

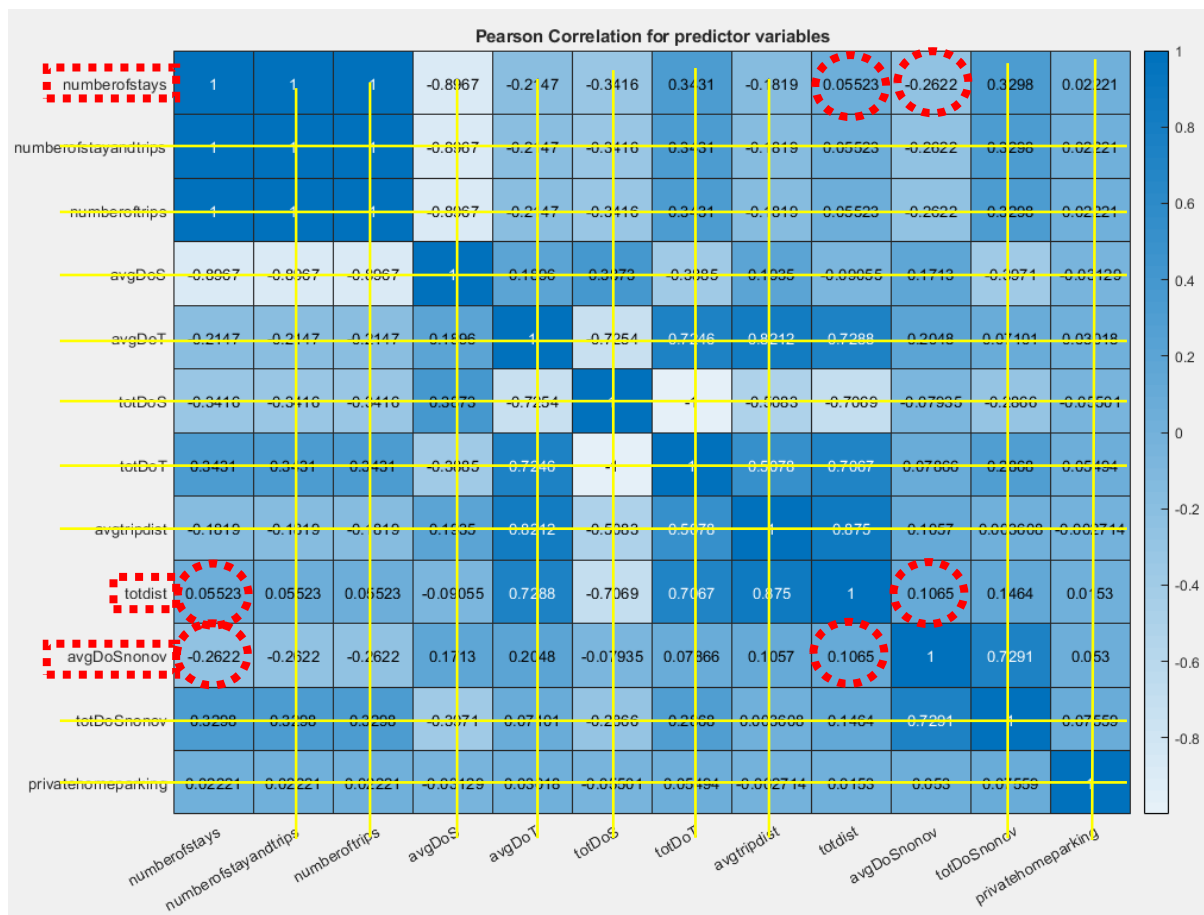


Figure 6.2 Pearson correlation coefficient and the selection of travel pattern characteristic variables to be used in the analysis. The selected variable correlations are circled in red, and the others are crossed in yellow.

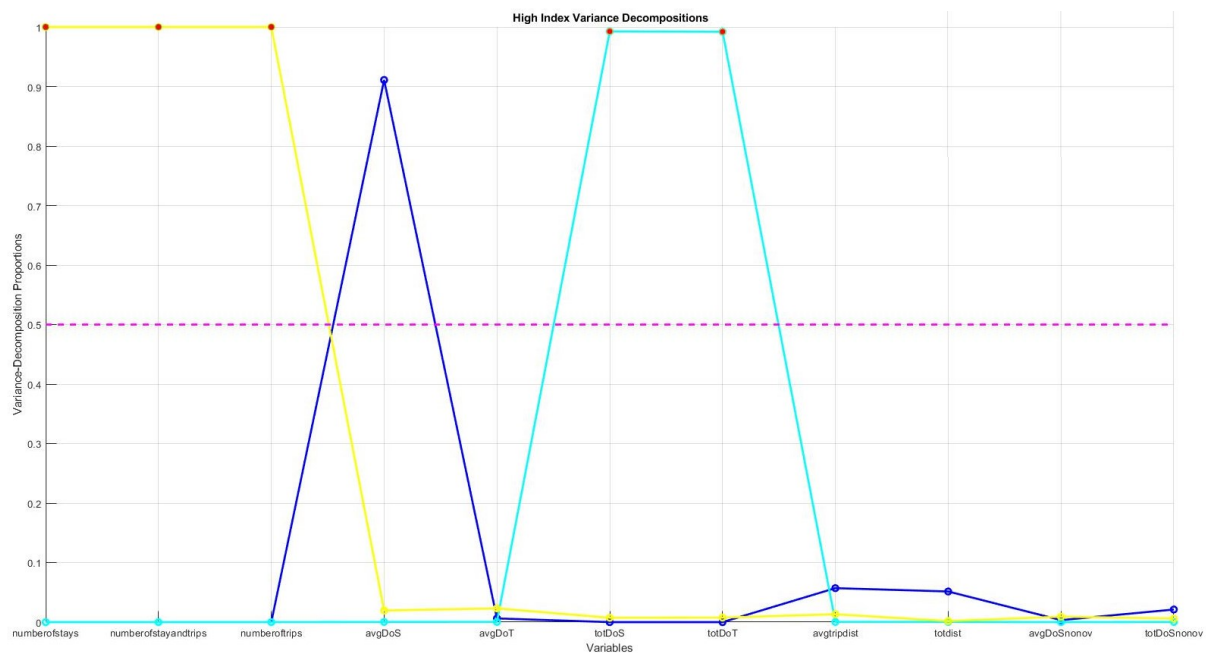


Figure 6.3 Collinearity between predictors. Purple line shows the tolerance level.

The reasons for selecting these variables were:

- Number of stays: represents the number of decision-making instances. This, together with average non-overnight DoS accounts for total amount of flexibility and decision-making time in the travel itinerary for the users.
- Total distance: represents the total amount of energy. This was chosen over average trip distance as the latter does not give the full representation of full energy needs/demands.
- Average non-overnight DoS: represents how much time and flexibility there is to make decisions at each decision instance. This was the average DoS of the stays which were not overnight. The reason the overnight DoS were excluded were because these tended to be very long (several hours), and were much longer relative to the other DoSs, which made the average much larger. It also stopped the average DoS capturing the average amount of time available for decision making and flexibility at each stay. The average non-overnight DoS of each stay was chosen over the total non-overnight DoS per day as the former puts the pressure of each decision-making instance into context and helps characterise the type of user and differentiate between those who make stays of short DoS or long DoS.

In the analysis, the variables were used as categorical variables. The categories for each variable are summarised on Table 6-3.

Table 6-3 Travel pattern variable summary

Variable	Type	Categories
Number of stays	Categorical	0-2, 3, 4, 5, 6, 7-9, 9-16
Total distance [km]	Categorical	<10, 10-15, 15-20, 20-30, 30-40, 40-60, 60-100, 100-200, 200-367
Average non-overnight DoS [mins]	Categorical	<20, 20-40, 40-400, 400-1050

6.1.2.1.2 Socioeconomic and socio-demographic indicators

The demographic variables of individuals used to analyse the distribution of the extent of financial benefits across the population were: income level, ethnicity, and employment status. These types of variables have been used in previous studies (Grisé and El-Geneidy, 2017; Schneider *et al.*, 2020).

Furthermore, for each borough of London, the average income levels, and index of multiple deprivation (IMD) were used to understand spatial distribution of the financial benefits and relationships with indicators of social welfare. These were both taken from the London Datastore (Greater London Authority, 2015; Ministry of Housing Communities & Local Government (MHCLG), 2019). IMD is a score ranging from 0 to 100 (most deprived) and is a measure of relative deprivation combining seven domains of income, employment, education and skills, health and disability, crime, housing and services, and living environment (Schneider *et al.*, 2020); it has been used in studies analysing equitable distribution across society (Schneider *et al.*, 2020).

A summary of the variables, their types and categories are in Table 6-4. The categories were dictated by the categories provided by the LTDS. The provided categories were grouped into these listed to have a more interpretable and less fragmented set of categories.

Table 6-4 Demographic variable summary

Variable	Type	Categories
Income (£)	Categorical	Missing, 5000-9999, 10000-14999, 15000-19999, 20000-24999, 25000-34999, 35000-49999, 50000-74999, 75000-99999, 100000+
Ethnicity	Categorical	Other, White, Mixed, Asian, Black
Employment status	Categorical	Other, Full time, Part time, Student, Unemployed, Retired, Looking after home or family

Borough average income	Continuous	N/A
IMD	Continuous	N/A

Of the 3,260 individuals used in the optimization, the number of individuals within each category of demographic variables, and the percentage of the total, are shown on Table 6-5.

Table 6-5 Number of individuals for each category of demographic variables.

Income (£)			Employment status			Ethnicity		
0-4999	57	1.75%	Other	71	2.18%	Other	87	2.67%
5000-9999	135	4.14%	Full-time	1897	58.19%	White	2257	69.23%
10000-14999	246	7.55%	Part-time	416	12.76%	Mixed	59	1.81%
15000-19999	234	7.18%	Student	57	1.75%	Asian	551	16.90%
20000-24999	269	8.25%	Unemployed	101	3.10%	Black	306	9.39%
25000-34999	439	13.4%	Retired	532	16.32%			
35000-49999	579	17.76%	Looking after home or family	186	5.71%			
50000-74999	566	17.36%						
75000-99999	292	8.96%						
100000+	443	13.59%						

6.1.2.1.3 Multicollinearity

To check for multicollinearity of the categorical variables, generalized variance inflation factor (GVIF) was used. Variance inflation factor (VIF) and GVIF measure the increase in variance compared to an orthogonal basis, with the coefficients indicating how much the coefficient is inflated for a variable due to its high correlation with at least one other variable.

The GVIF (Fox and Monette, 1992) is calculated for sets of related regressors, such as a for a set of indicator regressors for some kind of categorical variable, or for polynomial variables.

$$GVIF_1 = \frac{\det R_{11} \times \det R_{22}}{\det R} \quad [5]$$

For the categorical variables, the above equation gives one GVIF value for each separate category type. Therefore, variables which require more than one coefficient and thus more than one degree of freedom are typically evaluated using the GVIF. To make GVIFs comparable across dimensions, the following adjustment can be used (Fox and Monette, 1992).

$$GVIF^{\frac{1}{2DF}} \quad [6]$$

where DF (degrees of freedom) is the number of coefficients in the subset. This reduces the GVIF to a linear measure. It is analogous to taking the square root of the usual VIF.

GVIF was tested across the categorical variables representing travel pattern and demographic characteristics. A threshold of 10 is generally used as a sign of severe or serious multi-collinearity (O'Brien, 2007). There were no variables with high degrees of multicollinearity based on the values of GVIF calculated:

- Number of stays: 1.10
- Total distance: 1.02
- Duration of stay: 1.12
- Income: 1.02
- Ethnicity: 1.01
- Employment status: 1.03

6.1.2.1.4 Scenario parameters

The parameters which change across scenarios were included in the regression to ensure that the results were controlled for these parameters and to quantitatively analyse the effects of these parameters on the extent of an individual's financial benefit. From these results, insights on what an individual could gain if they had a certain configuration of these parameters could be gained. These parameters and their categories were:

- BEV capacity: 38.3kWh (Hyundai IONIQ), 40kWh (Nissan Leaf), 44.5kWh (MG ZS), 75kWh (Tesla Model Y)
- Number of days of optimization horizon: 1, 3, 5

- H2V: yes, no
- V2H: yes, no
- H2G: yes, no
- Residential energy price: fixed, real-time dynamic TOU half hourly average, real-time dynamic TOU half hourly low, real-time dynamic TOU half hourly high
- H2G price: real-time dynamic TOU half hourly average, real-time dynamic TOU half hourly low, real-time dynamic TOU half hourly high
- BESS capacity [kWh]: 0, 5, 10, 15, 45
- PV capacity [kW]: 0.3, 1, 3, 9
- PV season: summer, winter
- V2G: yes (real-time dynamic TOU half hourly), no

Only the BEV capacity was used as a regressor, rather than a combination capacity, range, and fuel economy. The reason was that because the BEV specifications are in sets, using a combination of specifications (capacity, range, fuel economy) would have led to one being linearly correlated to the other.

6.1.2.1.5 Other variables

Some variables were used in the regression to control for other important factors which could affect the extent of benefits. These were (with counts of each):

- Access to private off-street parking and usage during travel itinerary
 - Yes: 1,994
 - No: 1,266
- Household size
 - 1: 398
 - 2: 984
 - 3: 680
 - 4: 748
 - 5: 292
 - 6: 111
 - 7: 27
 - 8: 15
 - 9: 5

Whether the household had access to private off-street parking according to LTDS was also used as a regressor. This was used as this dictated whether the user could have V2H and H2V, this information was used to determine whether a person could connect their BEV to the home electricity system.

The household size from the LTDS was used to factor the overall residential energy demand, which could impact the extent of benefits a user could gain. Therefore, it was important to control for this variable in the regression.

These two variables were not used in the regression analysis for Formulation 1, as they had no relevance to the other variables being tested. Access to private off-street parking was obsolete as there was no energy transfer between the home and BEV enabled. Household size was obsolete as residential energy demand was not included.

6.1.3 Model reduction

The methodology outlined hereafter was used to reduce categories for each variable in the model. Two types of reductions were undertaken:

1. Reducing categories which were not statistically significant, and combining these with the reference group
2. Reducing categories which were similar to other categories within the same variable.

These two types of reductions are explained below.

For the first type, categories which had low t statistics and were not statistically significant were removed and combined with the reference group. When two categories were combined, the F test was used to prove whether the two estimates were statistically different at 5% significance level. This was done by testing the model with the combined categories as the null hypothesis, compared to the model with separate categories as the alternate hypothesis. The null hypothesis was tested for whether it could be rejected, or not rejected, based on whether the observed result may have happened by chance.

For the second type, the regression estimates of each category within each variable were considered. Where the regression coefficient of a category +/- its standard error overlapped on the regression coefficient of another category within the same variable, the two categories were combined, thus reducing the model. When two categories were combined, the F test was used, in the same manner as mentioned above.

These two types of reductions were performed in an iterative process for each model. After running the analysis to obtain t statistics, one category with the lowest t statistic was reduced (for either of the 2 types, whichever had the lowest t statistic). This process was then repeated until no categories were not statistically significant, and there were no categories which overlapped.

6.2 Results & discussion

The research questions, results, and discussions for each formulation are presented within the respective subsections in this section. The findings and discussions of the multivariate linear regression are based on the parameter estimates, t-statistics, and p-values of the explanatory variables of the regression model.

The results show the financial benefits an individual could gain by adopting the different combination of components of the integrated energy system, and the optimized use thereof. The individual is representative of a potential user in London, as the LTDS travel data for drivers was used to characteristics the travel patterns of the individuals used for the optimization. One perspective in interpreting the results and analyses which are averaged for each scenario is understanding it as what an average London driver could gain, should they adopt the specific technologies as defined by the scenario parameters. As outlined in the aims and objectives for the thesis, the model and analyses are undertaken in this research with distributional impact comparison intentions. As such, the low predictive ability of some of the models is not a concern (evidenced by some of the R^2 values in the models), given that the aim of the research was not for prediction.

The motivation for the results and discussion are to achieve RO2 as outlined in Section 1.2. Within the introductory section for the results and discussion of each formulation below, there is a reference to the specific RQs being answered by the respective formulations.

6.2.1 Overall results summary across all scenarios

The overall results for each formulation are presented on Table 6-6. The results show the positive financial benefits the optimization as a DST can have for individual users. Furthermore, the possibility of greater benefits from integration of the different components of the energy system, and the optimized energy management thereof can be seen. The evidence for the greater benefits is from the

fact that as each formulation added on more components, and there are increasing average benefits with each formulation.

Table 6-6 Overall results for all formulations.

	FORMULATION 1	FORMULATION 2	FORMULATION 3
FINANCIAL BENEFITS	£0.541	£0.627	£1.16
BENEFIT %	45.8%	222%	428%
BASELINE COST	£1.26	£0.923	£1.02
SCENARIOS	9	144	1,324
INDIVIDUAL DATA POINTS	29,340	469,440	4,316,240

6.2.2 Formulation 1 results and discussion

The results and discussions of Formulation 1 are presented in this subsection. The subsection presents several different topics. The discussion is ordered to first present the results and findings of the aggregated results from Formulation 1. Then the discussions on demographics topics are presented. Then the discussions on travel and BEV topics are presented.

The results and discussions in Formulation 1 addresses RQ1 and RQ3 (Subsection 2.4).

6.2.2.1 Effects of optimizing the charging scheduling on aggregated results across all scenarios in Formulation 1

Across all scenarios, on average compared to the baseline, an individual BEV user gained £0.541 per 1 day of travel itinerary compared to the baseline “dumb charging”. Multiplying by 365 days gives £197. The mean reduction in charging cost due to optimising the charging schedule was 45.8% reduction. The mean baseline cost was £1.26 per day. The mean optimized charging cost was £0.716. These results show the benefits of users using a DST for their BEV and residential energy management decision making. These values give an insight to how much an average London user could gain. The results averaged across all individuals for each of the nine scenarios are presented on Table 6-7.

The Gini coefficient was calculated across all the individuals’ financial benefits for each scenario. It shows the degree of inequality or dispersion of the benefits across each scenario within the population. There is very little change (~0.1%) across the first four scenarios which varies the BEV models. It is possible that segments of society will benefit differentially from adopting BEVs and optimizing the charging scheduling. It is important to understand how these benefits are distributed and whom it may favour.

Table 6-7 Average results for each of the scenarios of Formulation 1.

SCENARIO	BEV MODEL	NUMBER OF DAYS OF SIMULATION	FINANCIAL BENEFIT (£)	BASELINE COST (£)	BENEFIT %	GINI COEFFICIENT
1	Nissan Leaf	1	0.470	1.31	35.7%	0.721
2	Hyundai IONIQ	1	0.398	1.10	35.8%	0.724
3	MG ZS	1	0.534	1.50	35.6%	0.719
4	Tesla model Y	1	0.449	1.24	35.8%	0.726
5	Nissan Leaf	3	0.589	1.27	50.6%	0.692
6	Hyundai IONIQ	3	0.606	1.24	54.5%	0.678
7	MG ZS	3	0.522	1.04	54.8%	0.685
8	Tesla model Y	3	0.685	1.42	54.3%	0.676
9	Nissan Leaf	5	0.614	1.20	54.8%	0.699

The regression estimates for regression analysis of the scenario parameters using the financial benefit as the response variable are on Table 6-8. These will be discussed in the appropriate subsections below.

Table 6-8 Regression coefficients of scenario parameters analysed for the different scenarios for Formulation 1.

	VARIABLES	B	SE	T STAT	P VALUE
	Intercept	0.3877	0.0099	39.097	0.0000
BEV CAPACITY	Reference: 38.3				
BEV CAPACITY	40	0.0782	0.0125	6.238	0.0083
BEV CAPACITY	44.5	0.1498	0.0125	11.946	0.0013
BEV CAPACITY	75	0.0715	0.0125	5.702	0.0107
NUMBER OF DAYS	Reference: 1				

NUMBER OF DAYS	3	0.1235	0.0160	7.725	0.0045
NUMBER OF DAYS	5	0.1439	0.0089	16.221	0.0005
F statistics vs constant model	RMSE	R ²	Adjusted R ²		
84.6	0.0125	0.993	0.981		

6.2.2.2 *Spatial distribution of benefits and relationship with spatial welfare levels*

The benefits across all the scenarios were averaged for each borough. Figure 6.4 shows the spatial distribution of the average benefits of boroughs in London. Those who benefit more are those who live in South London, and further out from central London. A possible reason could be the different driving characteristics of users living in different boroughs, for example due to ease of usage of cars and access to parking. Our findings show that the benefits of optimizing BEV charging are distributed differentially spatially across boroughs in London. The one borough centrally in white is Westminster. There were no households in the LTDS 2015-16 dataset which were in Westminster, as mentioned previously in 5.1.1.

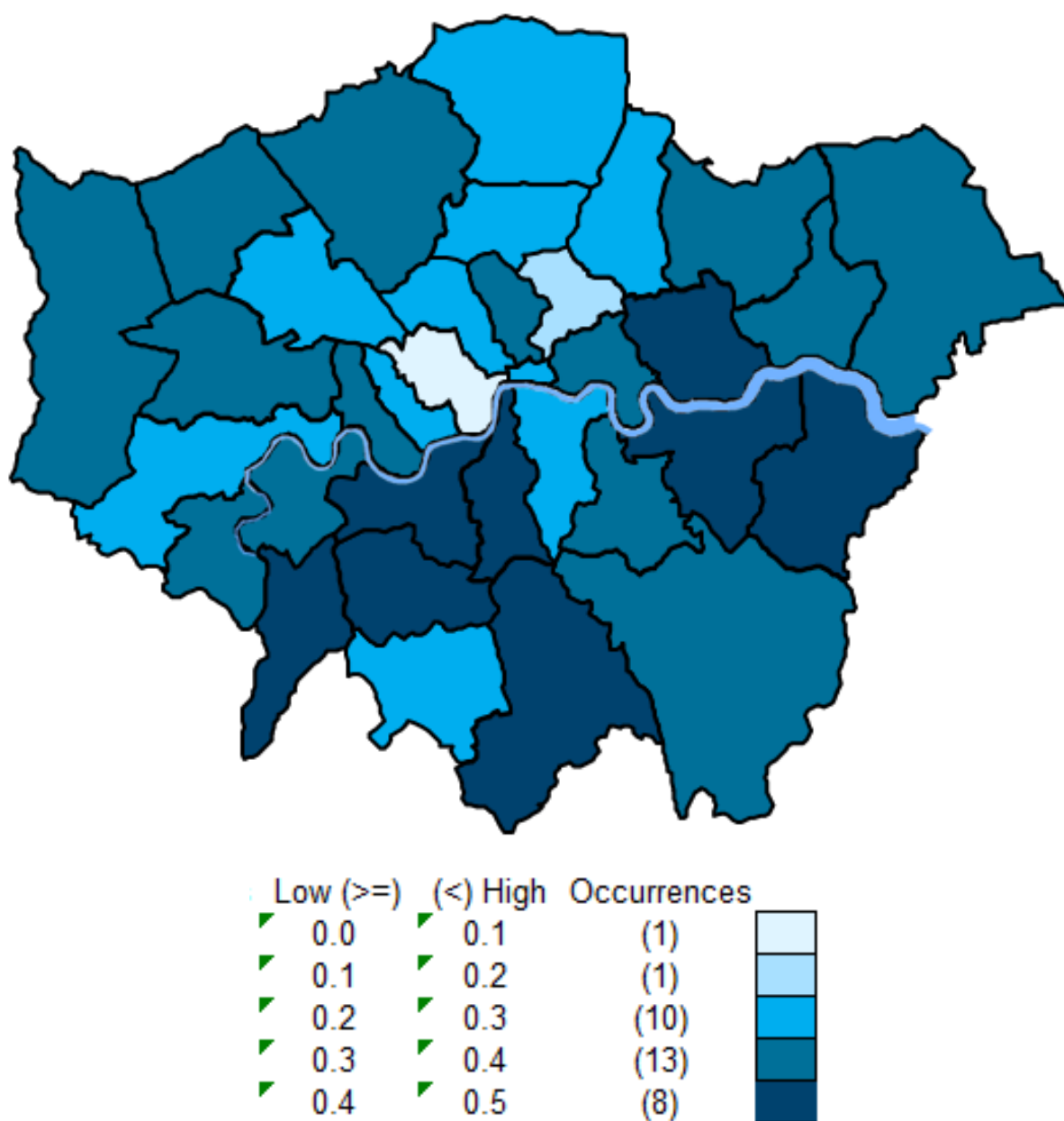


Figure 6.4 Spatial distribution of the benefits for each London borough averaged across all scenarios for Formulation 1.

The benefits across different boroughs were analysed against indicators of social welfare for each borough to ascertain whether there is evidence to suggest differential distribution of benefits across welfare levels spatially.

A weak negative linear correlation (-0.334) was found between the average benefit of boroughs and their respective borough average income (Figure 6.5). This could have suggested that those who live in worse boroughs in terms of deprivation i.e., higher IMD values may gain lower financial benefits from optimized BEV charging scheduling. However, the correlation was not statistically significant with p-value of 0.0619.

The correlation between average benefit of boroughs and their respective IMD were low (-0.0941; p-value: 0.608) and suggested no real relationship.

This suggests that to understand the potential differential benefits across society, further research not only in relationship of benefits with income, but also with other factors that make up deprivation, such as education and health, are important.

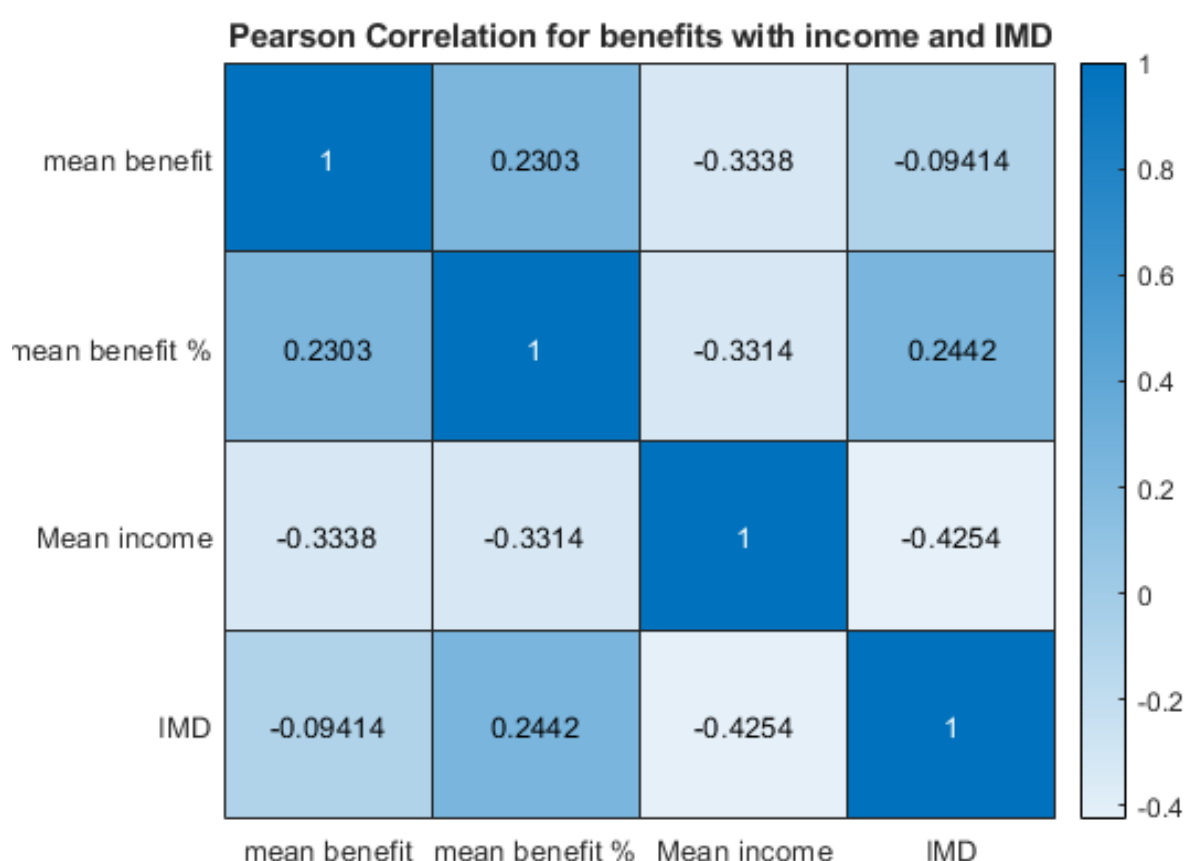


Figure 6.5 Correlation between benefit, borough average income and borough IMD for Formulation 1.

The analysis did not give evidence to suggest that there was differential distribution of the benefits of optimized BEV charging scheduling in London, which may disproportionately favour demographics that are already better off. The results from the analysis showed that spatially, those who live further away from the centre, and in the south gain lower benefits. However, no statistically significant correlation was found between the financial benefits and IMD of each borough, showing that those living in boroughs of higher social deprivation, would gain less financially.

6.2.2.3 Distribution of benefits across demographic characteristics

The differential distribution of benefits to individuals based on their demographics was analysed.

The benefits of each individual across all nine scenarios were regressed using the three demographic variables for each individual of household income, ethnicity, and employment status, and the two scenario parameters of BEV capacity and number of days. The regression estimates can be seen on Table 6-9. Results for each of the three demographic characteristics are presented first, then discussion and implications are presented.

Users with higher household income tended to gain greater financial benefits (Figure 6.6). However, the trend was not one of consistent increase with income, except for the very highest income category (£100,000+) gaining the most. The results for income brackets with their gain from the use of DST are presented in ascending order, relative to the reference category:

- £0-4,999 (reference category): £0.210
- £5,000-9,999: -£0.0662
- £10,000-£14,999: -£0.101
- £15,000-£19,999: +0
- £20,000-£24,999: +£0.0682
- £25,000-£34,999: +0
- £35,000-£49,999: +£0.0431
- £50,000-£74,999: +£0.0966
- £75,000-£99,999: +0
- £100,000+: +£0.0966

The difference between the highest and lowest gainers was stark, with the £50,000-£74,999 and £100,000+ income brackets gaining £0.198 more than the £10,000-£14,999 bracket, with respective gains of £0.307 and £0.109; this represents a 182% greater gain. It was interesting that those with higher incomes were not found to have continued increases. It was also interesting the dip in benefits for households with the lower incomes.

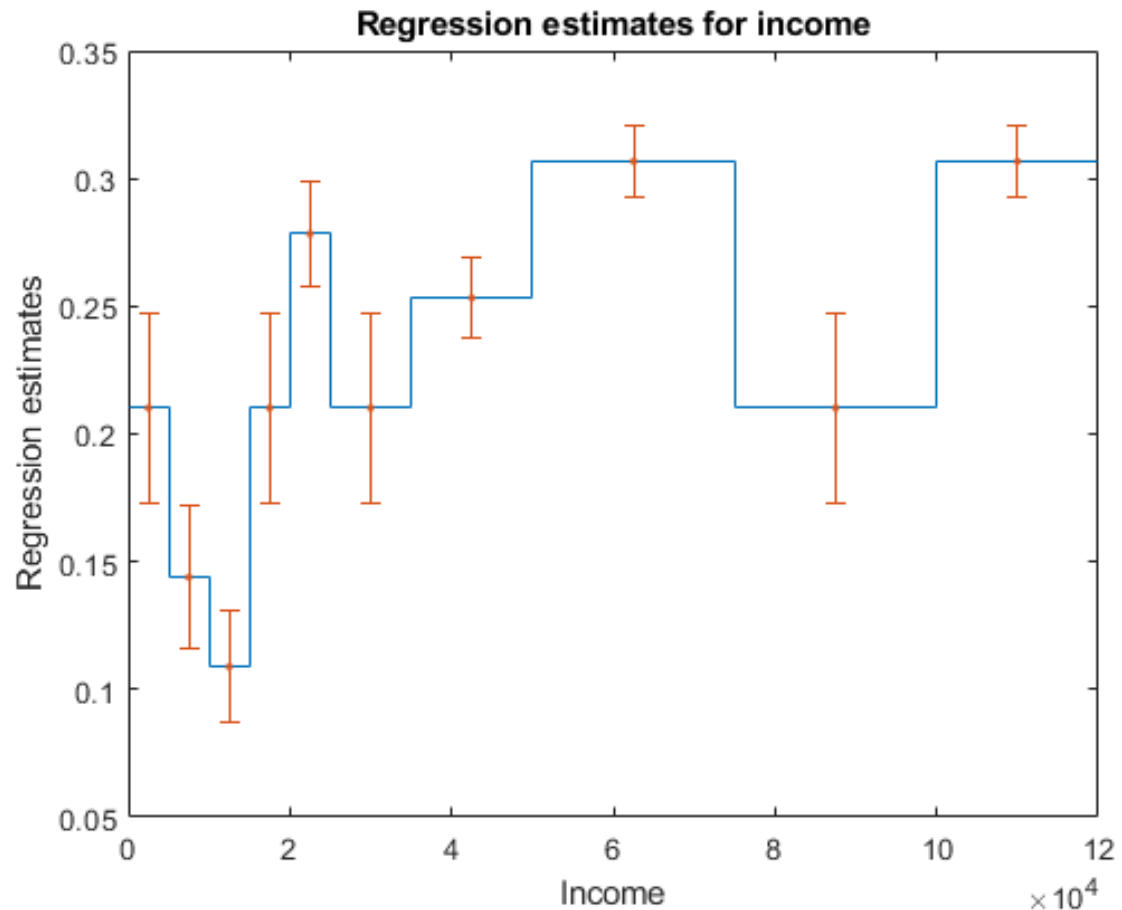


Figure 6.6 Regression coefficients for income with standard errors for Formulation 1.

The regression analysis showed there was some differential distribution across a few of the ethnicities (Figure 6.7). The results for ethnicities with their gain from the use of DST are presented relative to the reference category:

- Others (reference group): £0.210
- White & Black: +£0.128
- Asian & Mixed: +£0.0889

The regression analysis for employment status showed that there was differential distribution of the benefits across employment status, with a large difference between the highest and lowest of gainers.

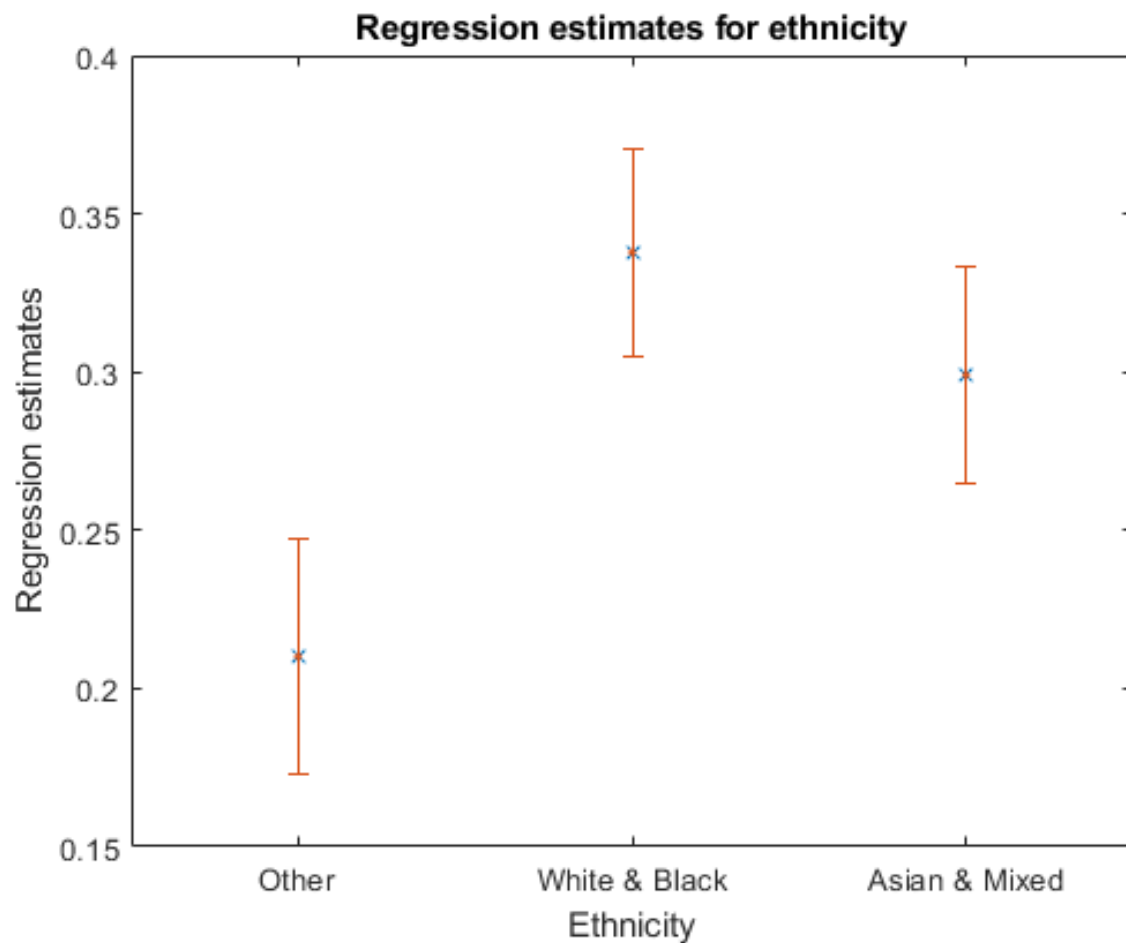


Figure 6.7 Regression coefficients for ethnicity with standard errors for Formulation 1.

The results for employment statuses with their gain from the use of DST are presented relative to the reference category:

- Others, part-time, students (reference group): £0.210
- Full-time: +£0.0920
- Unemployed: -£0.126
- Retired: -£0.0619
- Looking after home or family: -£0.207

There is a potential implication here that those who are not active in a full-time capacity in employment gain less. A hypothesis for the reason for the inequity in distribution is that this is due to their lower mobility leading to less need and therefore less potential for gains.

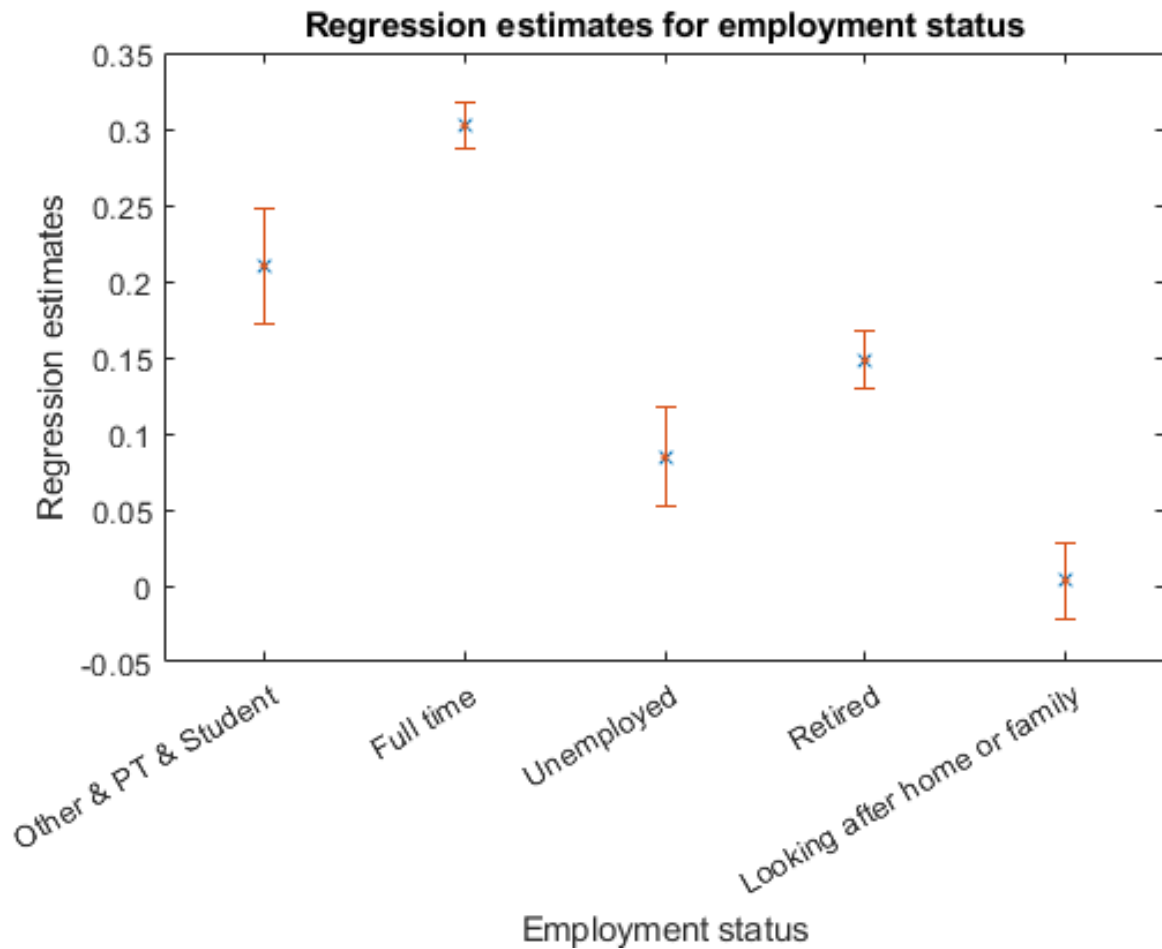


Figure 6.8 Regression coefficients for employment status with standard errors for Formulation 1.

Table 6-9 Regression estimates for demographic variables analysed across benefits of each individual across all scenarios for Formulation 1.

VARIABLES		B	SE	T	P VALUE
		STAT			
	Intercept	0.2101	0.0374	5.623	0.0000
HOUSEHOLD INCOME	Reference: 0-4999 & 15000-19999 & 25000-34999 & 75000-99999				
HOUSEHOLD INCOME	5000-9999	-0.0662	0.0281	-2.360	0.0183
HOUSEHOLD INCOME	10000-14999	-0.1013	0.0217	-4.677	0.0000
HOUSEHOLD INCOME	20000-24999	0.0682	0.0207	3.300	0.0010

HOUSEHOLD INCOME	35000-49999	0.0431	0.0157	2.742	0.0061
HOUSEHOLD INCOME	50000-74999 & 100000+	0.0966	0.0136	7.122	0.0000
ETHNICITY	Reference: Others				
ETHNICITY	White, Black	0.1277	0.0330	3.876	0.0001
ETHNICITY	Asian & Mixed	0.0889	0.0346	2.573	0.0101
EMPLOYMENT STATUS	Reference: Other & Part-time & Student				
EMPLOYMENT STATUS	Full-time	0.0920	0.0149	6.185	0.0000
EMPLOYMENT STATUS	Unemployed	-0.1258	0.0328	-3.831	0.0001
EMPLOYMENT STATUS	Retired	-0.0619	0.0186	-3.336	0.0009
EMPLOYMENT STATUS	Looking after home or family	-0.2069	0.0256	-8.083	0.0000
F vs constant model	RMSE	R ²	Adjusted R ²		
49.2	0.902	0.0261	0.0256		

The results show that there was differential distribution of financial benefits across demographics, by household income, ethnicity and by employment. The most pressing result is that those of lower income and those not in full time employment gain less, which means not only are they already worse off financially, they have less opportunity to gain through optimized BEV charging and BEV adoption.

If equitable distribution is desired, policies which help balance the distribution of benefits may be necessary. A suggestion is to implement policies that aid easier availability and access of BEVs and optimized BEV charging to those who have been found to gain less. Another would be policies aimed at tackling the inherent reasons why certain demographics gain less and amending them. It would be important to understand what underlying reasons contribute to this disparity. Greater attention to the disparity in benefits gainable by the different demographics should be given when considering policies impacting BEV adoption.

6.2.2.4 Effects of travel pattern characteristics on the extent of benefits

The effects of travel pattern characteristics on the benefits to individuals were analysed.

The benefits of each individual across all nine scenarios were regressed using the three travel pattern characteristic variables for each individual of number of stays, total travel distance, and the average duration of stay, and the two scenario parameters of BEV capacity and number of days. The regression estimates can be seen on Table 6-10.

Those with greater number of stays, total distances, and average duration of stay gained more (Figure 6.9, Figure 6.10, Figure 6.11). A hypothesis is that with greater number of stays, there is more variability of prices and therefore greater potential to harness the opportune prices. With longer total distances, the overall demand and therefore cost of the electricity would be greater, therefore the impact on savings from the optimization could be greater.

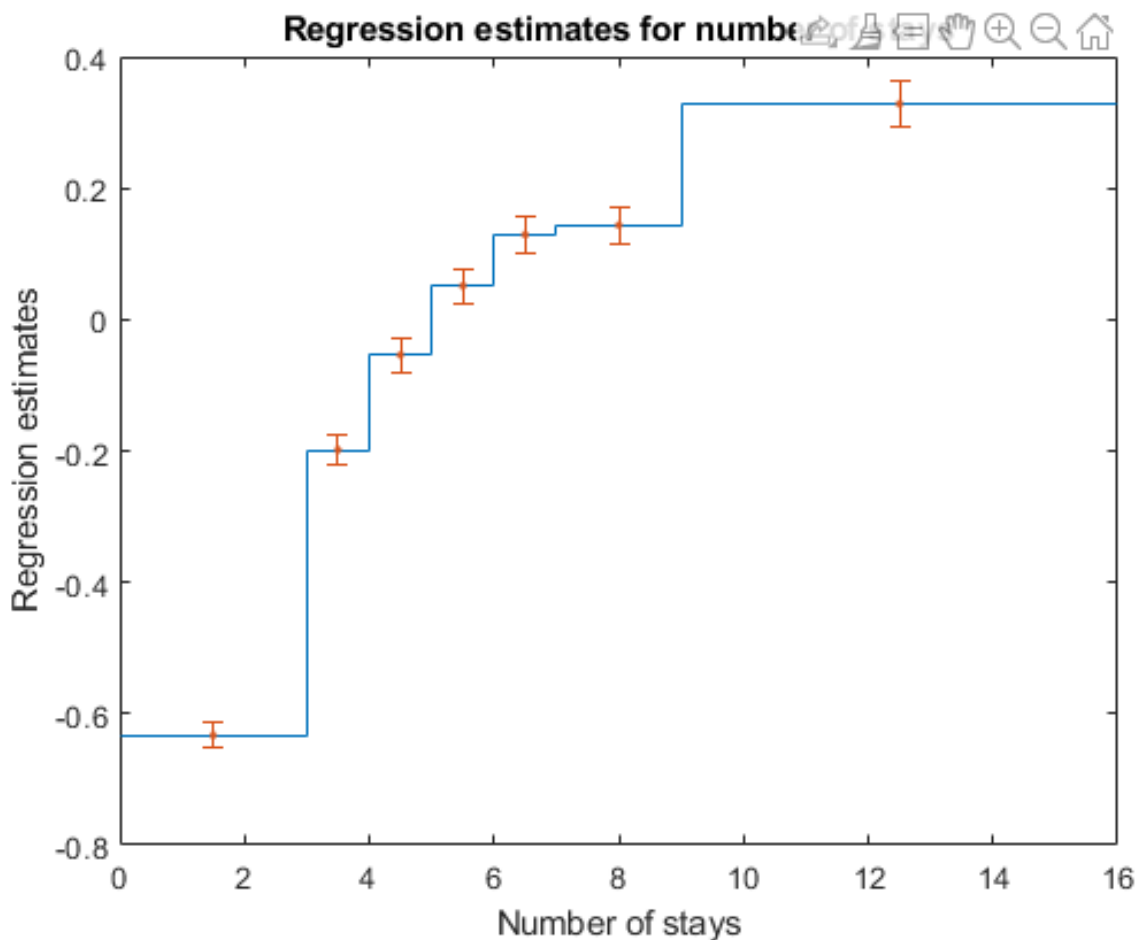


Figure 6.9 Regression estimates for number of stays with standard errors for Formulation 1.

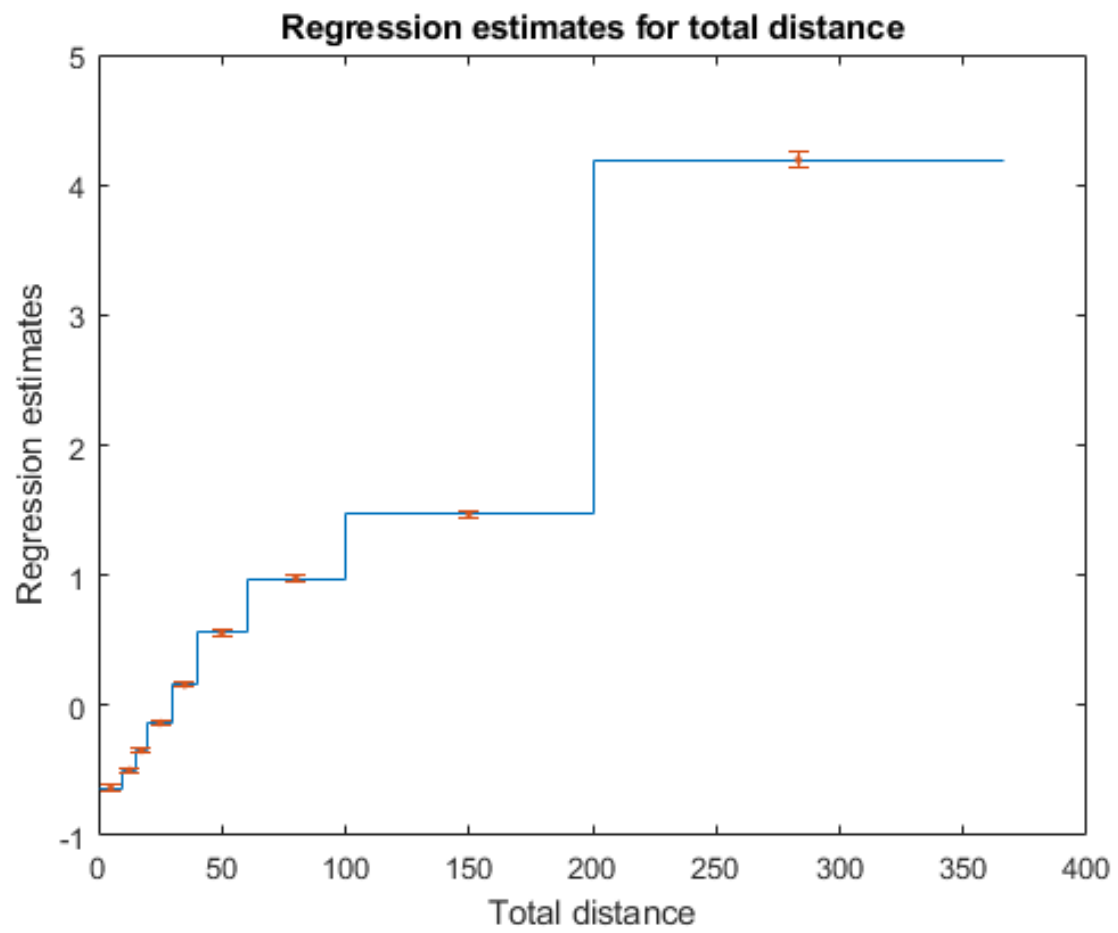


Figure 6.10 Regression estimates for total distance with standard errors for Formulation 1.

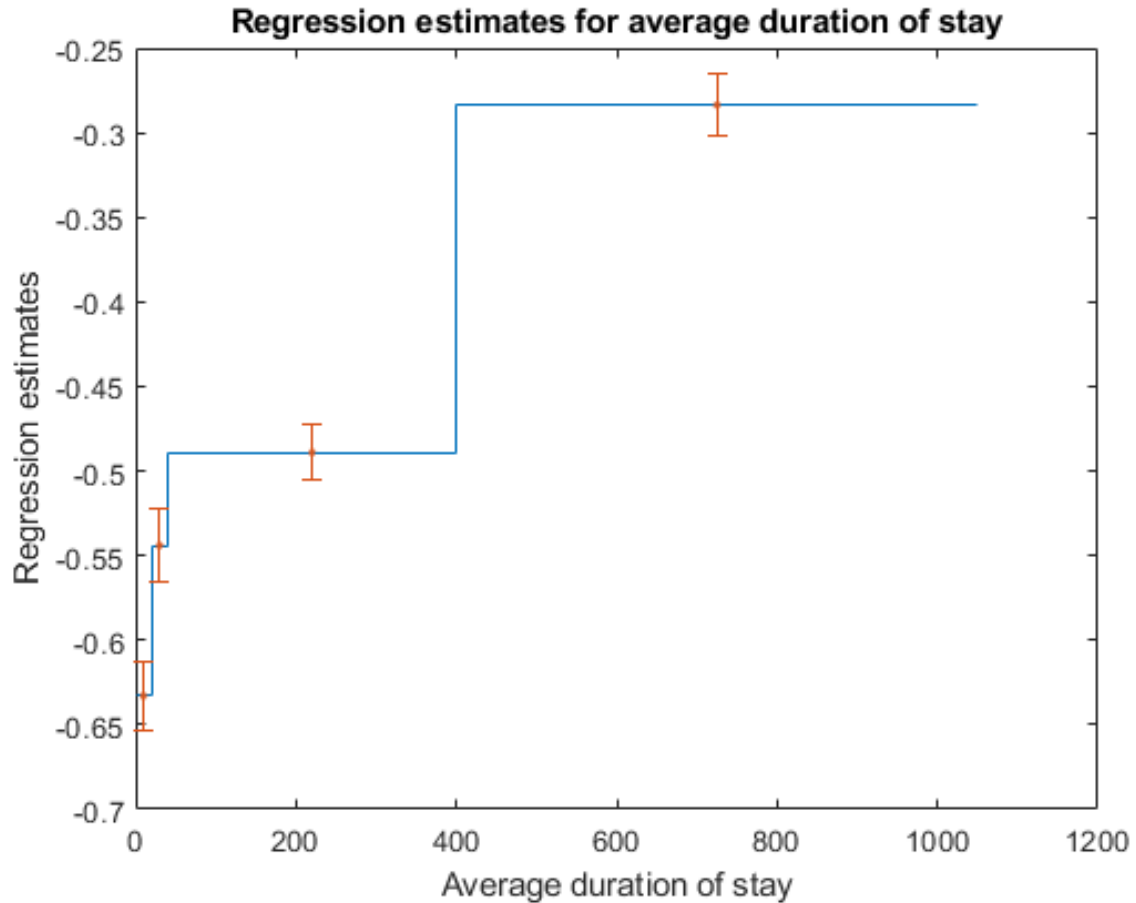


Figure 6.11 Regression estimates for average duration of stay with standard errors for Formulation 1.

The implication is that drivers with more complicated travel itineraries should be made aware of the potential for financial benefits of using an optimized charging scheduling DST. Any DST should target uptake from these users to offer great value. The results confirmed the hypothesis that users with more complicated and longer travel itineraries could gain more from the optimization streamlining the decision-making process.

Table 6-10 Regression estimates for travel pattern variables analysed across benefits of each individual across all scenarios for Formulation 1.

	VARIABLES	B	SE	T STAT	P VALUE
	Intercept	-0.6330	0.0201	31.549	0.0000
NUMBER OF STAYS	Reference: 0-2				
NUMBER OF STAYS	3	0.4347	0.0236	18.395	0.0000
NUMBER OF STAYS	4	0.5790	0.0257	22.544	0.0000
NUMBER OF STAYS	5	0.6841	0.0257	26.649	0.0000

NUMBER OF STAYS	6	0.7622	0.0292	26.061	0.0000
NUMBER OF STAYS	7-9	0.7765	0.0283	27.475	0.0000
NUMBER OF STAYS	9-16	0.9613	0.0349	27.562	0.0000
TOTAL DISTANCE	Reference: <10				
TOTAL DISTANCE	10-15	0.1341	0.0115	11.609	0.0000
TOTAL DISTANCE	15-20	0.2869	0.0141	20.398	0.0000
TOTAL DISTANCE	20-30	0.4973	0.0131	38.027	0.0000
TOTAL DISTANCE	30-40	0.7917	0.0180	43.998	0.0000
TOTAL DISTANCE	40-60	1.1911	0.0188	63.191	0.0000
TOTAL DISTANCE	60-100	1.6072	0.0209	77.071	0.0000
TOTAL DISTANCE	100-200	2.1049	0.0249	84.404	0.0000
TOTAL DISTANCE	200-366.57	4.8262	0.0590	81.849	0.0000
AVERAGE DURATION OF STAY	Reference: <20				
AVERAGE DURATION OF STAY	20-40	0.0889	0.0215	4.138	0.0000
AVERAGE DURATION OF STAY	40-400	0.1440	0.0161	8.952	0.0000
AVERAGE DURATION OF STAY	400-1050	0.3494	0.0180	19.372	0.0000
F statistics vs constant model	RMSE	R ²	Adjusted R ²		
1240	0.658	0.482	0.658		

6.2.2.5 Effects of BEV specifications on the extent of benefits

The effects of BEV capacities on the benefits to individuals was analysed.

The benefits of each individual across all nine scenarios were regressed using the BEV capacity and number of days, as well as all travel and demographic characteristics as control. The regression estimates are on Table 6-8.

Higher capacities of BEVs generally yielded better benefits (Figure 6.12), with the MG ZS with capacity of 44.5kWh gaining £0.150 more than the Hyundai IONIQ with 38.3kWh. However, it seems it is not a simple case of larger capacity leading to greater benefits, as the Tesla Model Y with 75kWh did not have the best benefit (£0.0715 higher benefits than the reference Hyundai IONIQ). There may be some

intricacies in the interplay between BEV capacity, fuel economy and range which requires further researching. The evidence for this is that whilst all four BEV specifications used had fuel economies not too dissimilar from each other, the Tesla Model Y had a capacity, and therefore range, almost double that of others. A possibility is that BEVs with higher capacities tend to give better benefits, when their ranges are relatively similar to each other (and by implication, having lower fuel economies). A hypothesis is that higher capacity yielding higher benefits is due to having to purchase more electricity to fulfil their mobility needs, increasing the overall baseline charging cost, and thus greater savings from optimization. To check for this, further analysis based on baseline charging cost, and benefit % was conducted. Table 6-7 above showed the baseline charging cost for the different BEV specifications. It confirms the hypothesis that higher BEV capacities do lead to higher overall charging costs, except in the case of the Tesla Model Y. Regression analysis using the benefit % as the response variable showed marginal differences between the four models; the estimates ranged from -0.036% to -0.003%. These results show that the higher financial benefits for higher capacity BEVs are proportional to the increase in baseline operating cost.

The implication is a DST can be very useful. Even though owners with higher capacity BEVs would incur higher baseline cost from charging, the DST helps balance the increase in cost for users by providing proportionately higher financial benefits, such that they still get the same % benefit. However, there is no additional benefit from purchasing BEVs with higher capacities, and the users would have to contend with the increased charging costs that come with it.

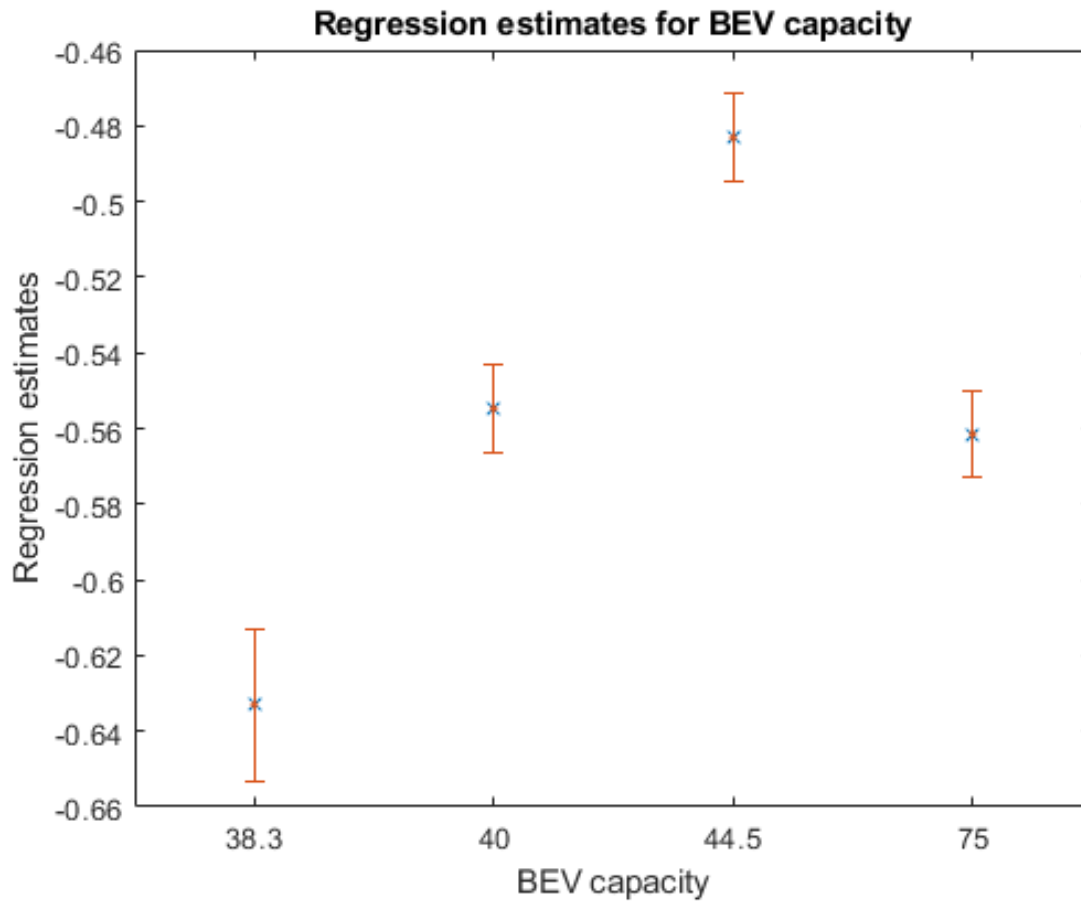


Figure 6.12 Regression coefficients for BEV capacity with standard errors for Formulation 1.

6.2.2.6 Effects of longer optimization time horizons

The results averaged across all individuals for each of the nine scenarios were presented on Table 6-7. The results show that as the number of days of simulation is increased, the savings on a per day basis increased (Figure 6.13). For the Nissan Leaf, there is a 25.3% increase at three days simulation compared to one day simulation, and 4.24% increase at five days compared to three. This shows that there is more benefit to planning further ahead in charging scheduling to harness the opportune charging costs. The results also show that the increase in benefits diminish as the optimization time horizon increases.

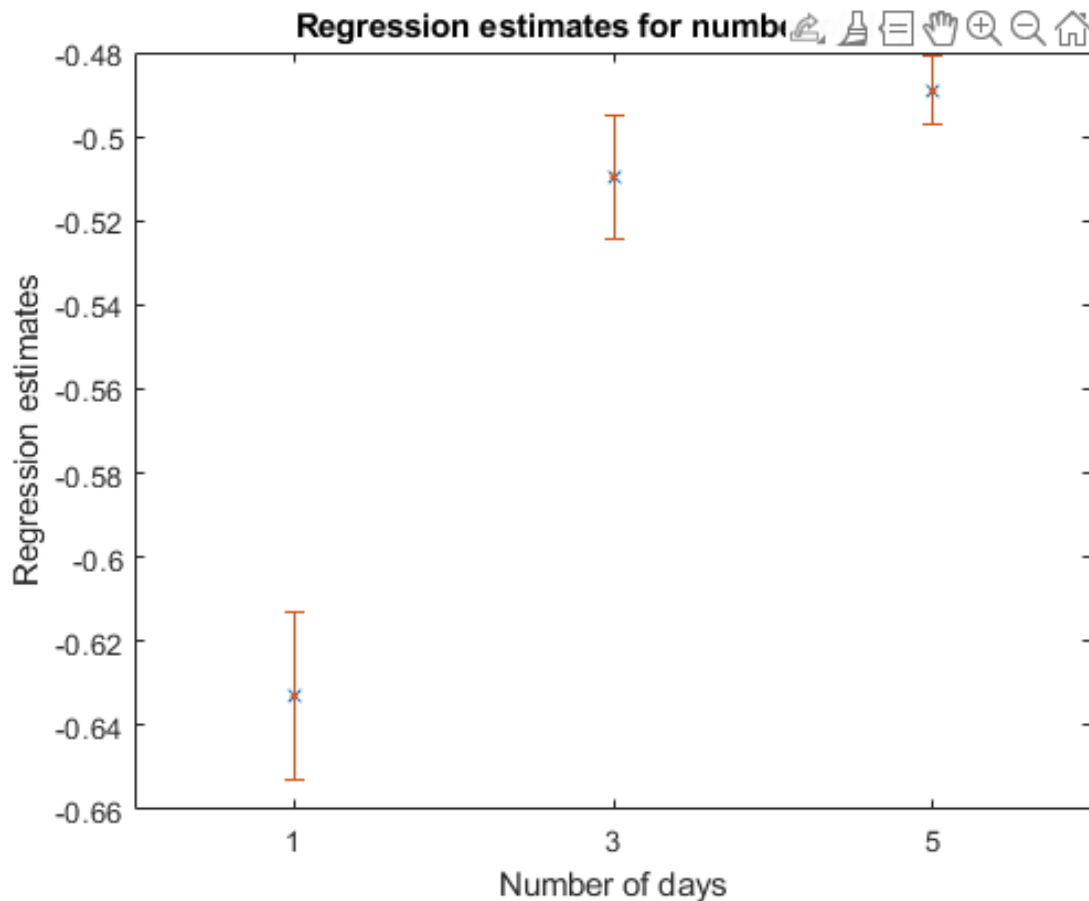


Figure 6.13 Regression estimates for number of days with standard errors for Formulation 1.

These findings are reasonable. The benefits should increase if the scheduling is optimized further into the future, as the cheaper charging cost opportunities can be harnessed to replace more of the more expensive charging locations. The increasing benefits should diminish as the longer the time horizon gets, the fewer expensive charging locations there are to replace, until eventually there aren't any.

The implications are twofold. One is that it is likely the planning aspect that can be the challenge for many BEV users, as the planning aspect is what any person of society has trouble doing, and must spend time to do so, making it easy to simply not plan ahead. Examples can be purchasing travel tickets or convenience subsistence ahead of time, instead of paying a premium for impulse or convenience purchases. The second implication is that users should be encouraged to plan their charging scheduling ahead of time. They should be made aware of the potential financial savings. This research has shown and quantified the potential savings. The DST presented in this research can aid users achieve these financial benefits.

The significance of enabling the savings is to free up the finances of users. The saved money can then be used by users for other uses, which may add greater value, such as in education, or skill

development. Another significance is that the savings are likely to benefit those of lower incomes higher in relative terms. This is due to the evidence found in the literature that those of lower incomes spend higher proportions of their income on energy costs. Therefore, saving energy costs will free up a higher proportion of incomes for those of lower income.

6.2.2.7 Formulation 1 summary

The findings for Formulation 1 are summarised here. The quantitative analysis showed some evidence of differential distribution of financial benefits of optimized BEV charging across demographics. The distribution was analysed across several indicators. The insights from the analysis can guide further actions to ensure equitable adoption of BEVs.

Analysis across demographics show that there was inequity at an individual level, identifying potential indicators of differential distribution of benefits. Furthermore, there was evidence of unequal distribution of the benefits spatially. The analysis yielded some indicators which might not lead to differential distribution. These key results are summarised below in Table 6-11, then implications follow below the table.

Table 6-11 Summary of key results from Formulation 1.

Key finding	Numerical result (per day)
Higher household income individuals gaining higher benefits.	+£0.198
White and black ethnicities gaining higher benefits	+£0.1277
Those in full-time employment gaining higher benefits	+£0.299
Those with longer, more complex travel itineraries (in terms of number of stays, total travel distance, and average duration of stay) gain higher benefits	+£0.134-4.83

The implication from the finding that those with higher household incomes gained more benefits means there is potential for inequity of distribution of the benefits. Furthermore, those in full-time employment, and more likely to be financially stable, also gained more. This means that those with lower income, or not in full time employment are likely in worse financial situations, and have less opportunity to gain through optimized BEV charging and BEV adoption. This can exacerbate the equity of distribution of wealth. Understanding why those with higher household incomes, and in employment, gained higher is an important next step. A suggestion is that those who are better financially have a mobility pattern which has more instances of opportune charging available.

The insights from this research should inform policy planning for BEV adoption and users. If equitable distribution is desired, policies which help balance the distribution of benefits may be necessary. The demographic characteristics and welfare levels of local areas of potential BEV users that policies would implicitly target should be carefully considered. Alternatively, policies that differentially affect segments of society could be planned to counter the differential benefits shown by this research. For example, subsidies for purchasing BEVs could be based on income, or by home location, or a combination of the two.

Further research using travel itinerary data of multiple days would yield more accurate extent of benefits, and therefore aid in more accurately identifying the demographics at risk of unequal distribution of the benefits of optimized BEV charging scheduling. Further research involving relationship between benefits and different types of deprivation, such as education or health, could yield better indication of types of areas that are at greater risk of inequity.

6.2.3 Formulation 2 results and discussion

The results and discussions of Formulation 2 are presented in this subsection. The subsection presents several different topics. The discussion is ordered to first present the results and findings of the aggregated results from the formulation. Then the discussions on the elements added in Formulation 2 are presented. Then the discussions on demographics topics are presented. Then the discussions on travel and BEV topics are presented.

The results and discussions in Formulation 1 addresses RQ1, RQ2, and RQ3 (Subsection 2.4).

To enable drawing the appropriate insights, the analysis was performed in two different ways. One of the ways was performing the regression analysis on the results of individuals. The other way was by performing the regression analysis on the results of the scenarios; this involved using average benefits for each scenario across all the individuals within the respective scenarios. Each subsection will restate whether the discussion is based on the analysis of the individuals or scenarios. The analyses based on individuals were:

- Distribution of benefits across demographics
- Effects of travel pattern characteristics

The analyses based on scenarios were:

- Effects of optimizing the charging and energy management
- Effects of real-time dynamic TOU residential energy tariffs

- Effects of integration with the grid

In the case of analysis performed on individuals, the 3,260 individuals' respective benefits for each of the 144 scenarios from Formulation 2 and the nine scenarios from Formulation 1 were used. The regressors were the appropriate individual characteristics for travel pattern characteristics and demographic characteristics. These regressors were chosen to enable answering research questions. The scenario parameters were included as regressors to account for the effects of those. These scenarios parameters were BEV capacity, H2V, V2H, real-time dynamic TOU, and H2G. Furthermore, the household size of individuals was included, again to control for effects of those.

In the case of analysis performed on the scenarios, the total 153 scenarios from Formulation 1 and Formulation 2 were used, with regressors of: BEV capacity, H2V, V2H, real-time dynamic TOU, and H2G. The scenario respective average benefits of all individuals across all scenarios were regressed using the regressors.

6.2.3.1 *Effects of optimizing the charging scheduling on aggregated results across all scenarios up to Formulation 2*

Across all scenarios, on average compared to the baseline, an individual BEV user gained £0.626 per 1 day of travel itinerary compared to the baseline "dumb charging". Multiplying by 365 days gives £228. The mean reduction in energy cost due to optimising the charging schedule and energy management to the user of the BEV and residential energy needs was 222%, meaning 100% savings with an additional 122% of the baseline cost as income. The mean baseline cost was £0.923 per day. The mean optimized charging cost was £0.307. These results show the benefits of users using a DST for their BEV and residential energy management decision making. These values give an insight to how much an average London user could gain. The average benefits for Formulation 2 are higher than for Formulation 1. This suggests that the benefits from the added components for Formulation 2 has potential for greater benefits.

Table 6-12 shows the regression estimates for scenario parameters analysed across average benefits across all scenarios. Access to V2H, TOU tariffs, and H2G have a positive effect on the benefits, and these positive effects are evidenced. These will be further discussed in the subsequent subsections.

Table 6-12 Regression coefficients of scenario parameters analysed for the different scenarios for Formulation 2.

	VARIABLES	B	SE	T STAT	P VALUE
	Intercept	0.2459	0.03766	6.53	0.0000
BEV CAPACITY	Reference: 38.3				

BEV CAPACITY	40	0.0512	0.02869	1.79	0.0763
BEV CAPACITY	44.5	0.1021	0.02869	3.56	0.0005
BEV CAPACITY	75	0.0780	0.02869	2.72	0.0074
NUMBER OF DAYS	Reference: 1				
NUMBER OF DAYS	3	0.2923	0.13062	2.24	0.0268
NUMBER OF DAYS	5	0.2952	0.04958	5.95	0.0000
H2V	Reference: no				
H2V	Yes	-0.2906	0.03896	-7.46	0.0000
V2H	Reference: no				
V2H	Yes	0.6650	0.02198	30.26	0.0000
RESIDENTIAL ENERGY PRICE	Reference: one price tariff				
RESIDENTIAL ENERGY PRICE	Dynamic TOU average	0.1247	0.02821	4.42	0.0000
RESIDENTIAL ENERGY PRICE	Dynamic TOU low	0.1314	0.02917	4.50	0.0000
RESIDENTIAL ENERGY PRICE	Dynamic TOU high	0.1590	0.02917	5.45	0.0000
H2G PRICE	Reference: no H2G				
H2G PRICE	H2G average price	0.2438	0.03089	7.89	0.0000
H2G PRICE	H2G high price	0.2951	0.03127	9.44	0.0000
H2G PRICE	H2G low price	0.1946	0.03127	6.22	0.0000
F vs constant model	RMSE	R ²	Adjusted R ²		
95	0.125	0.899	0.889		

6.2.3.2 Effects of real-time dynamic half-hourly TOU residential energy tariffs on extent of benefits

The analysis suggests that access to TOU tariffs can be financially beneficial to BEV users, from opportunistic usage of times of cheaper energy prices. The analysis was performed across scenarios. The regression estimates for enabling real-time dynamic half-hourly TOU residential tariffs was £0.125, with a higher benefit of £0.159 for higher priced TOU tariff, and slightly lower benefit of £0.131 for lower priced tariff (Table 6-12). The benefits are shown to be a high proportion of the baseline cost of

£0.923, meaning significant cost reductions. The overall benefits for the average, high, and low TOU tariffs are £0.371, £0.405, and £0.377 respectively. To put these into perspective against the baseline cost, the TOU tariffs represent cost reductions of 40.1%, 43.9% and 40.9% respectively. At first look, the results are promising, with higher benefits achievable by the DST for users when the prices are higher. However, similar to the effects of larger BEV capacities on higher benefits (Subsection 6.2.2.5), the reason for higher prices leading to higher benefits could be due to the overall energy cost for users increasing across the board, for both baseline and optimized with the DST. This could have resulted in an inflated set of baseline cost, optimized cost, and therefore the benefits. To check for whether the higher benefits are due to higher prices across all scenarios, further analysis of benefit % was conducted by using the benefit % as the response variable for the regression. The analysis showed that the caveat can be rejected, and there are indeed proportionately higher benefits achievable as prices increase. The regression coefficients evidenced that compared to the reference of fixed tariff of -12.5% points, the TOU tariff had benefits % that was 79.6% points higher (overall 92.1% points higher benefit), the low TOU was 85.4% points higher, and the high TOU was 101% points higher. A hypothesis for the higher benefits and benefit % attainable by the DST at higher energy prices is that the DST is able to better harness the opportune times of low energy, increasing the proportional benefit. This is evidence supporting the advantages of access to both the DST and TOU tariffs. Indeed, the DST is shown to be even more valuable at times of higher energy prices, without which the users would be at the mercy of higher costs of energy, without being able to make the best of the situation through optimizing the times of use of energy through the DST.

The implications of this analysis are that TOU alongside a DST can have financial benefits for BEV users with respect to their overall energy bills, both BEV charging and residential energy use. Furthermore, the analysis suggests there can be benefits to the wider energy network. The benefit can be from grid load balancing. Load balancing would take place with a user using the DST. The DST would naturally advise the user to use energy for optimal cost. With the understanding that the varying TOU prices implicitly indicate times of stresses on the grid, the user would be load balancing. The insight into potential stimulation of load balancing by users is key evidence to support the potential of synergy of BEV, DST and TOU for providing benefits to the energy system.

To attain these benefits, governments could implement policies to speed up adoption of smart meters and real-time dynamic half-hourly TOU residential energy tariffs, using existing businesses, such as Octopus Energy, as models. This could be in the form of incentives for energy providers, or individuals who adopt TOU tariffs. Raising awareness of the benefits of access to TOU alongside BEVs for current owners of BEVs or not, should be an objective to aid in BEV adoption, and the wider societal benefits of BEV adoption as mentioned previously in this thesis.

Businesses providing or enabling TOU tariffs could similarly raise awareness of these financial benefits to users to make their products more attractive and aid their business models. The provision of TOU tariffs would also aid in achieving the wider societal benefits of BEV adoption by increasing availability of TOU tariffs to consumers and stimulating other competing businesses to also provide these services. The wider adoption from businesses would stimulate wider adoption by users, and thus great instances of the benefits for society.

6.2.3.3 Effects of integration with grid and home via V2H, H2V, H2G on the extent of benefits

The results and analysis of the effects of H2V, V2H and H2G on the extent of benefits are presented. These analyses were performed across scenarios.

H2V

The regression estimate for enabling H2V was -0.291 (Table 6-12). For clarity, the benefits of H2V as modelled in this thesis is the ability to charge the BEV at residential energy prices via a home charger, which is the cheapest price available, other than the free public charging locations available. It was interesting that compared to the reference of not having H2V enabled that it had a negative effect on the extent of benefits. Added on with the intercept gave a value of -0.045 $(-0.291+0.246)$. T-test was performed to check whether the effect of H2V on overall benefits was different from 0, by using the null hypothesis that the value of the H2V parameter is not significantly different from -0.246. If the estimate was -0.246, this added on to the intercept value would yield 0. The t-test value was -1.15 $([-0.291-(-0.246)]/0.0390)$, therefore the estimate for H2V is similar to -0.246 which would yield an overall benefit of having H2V as 0. A hypothesis for the possible reason for lack of positive effect on the benefits is that this access to cheaper prices brings down the overall cost for both baseline and optimized costs. This then leads to a lower extent of benefit, since the savings would be lower due to the overall lower costs involved in charging the BEV. To check this hypothesis, regression analysis with the benefit % as the response variable was performed. The evidence supported the hypothesis; the regression estimate for enabling H2V was -89.3%, suggesting that there is a proportional decrease in benefits. To further test the hypothesis for the reason for the lack of positive effect of H2V on benefits, further work in crosschecking the scenario average baseline cost to see if indeed the baseline cost does decrease for scenarios with H2V disabled could yield more insights. A further analysis that could be conducted is analysing the interaction between access to home parking for individuals and availability of H2V, as only those individuals with access to home parking would actually be able to charge at residential energy prices.

If indeed the access to H2V does decrease the baseline cost for all users with and without the DST, this has significant implications for BEV users. The implications are that BEV users could benefit

financially from having access to H2V. This finding can aid BEV adoption as it shows a financial incentive for potential BEV adopters, without them having to take significant action that deviates from their normal schedule. In fact, the action needed to take advantage is one that is a source of added convenience for them. The added convenience is by installing and being able to charge whilst at home. The challenges from barriers of BEV adoption of difficulty of making charging decisions, access to chargers, and total cost of ownership of BEVs could be ameliorated if more potential BEV users could have home chargers installed.

To aid in making access to H2V for users a reality, governments could implement policies to subsidise home chargers to aid BEV adoption. This research shows that there is evidence to support that access to home chargers further decrease the cost of charging of BEVs, on top of the already widely known fact that BEVs have lower fuel charge compared to ICEVs; with home chargers, the cost of fuel for BEVs compared to ICEVs would be even lower.

Furthermore, this analysis shows that businesses providing home charger installation can also spread awareness of the added value of home chargers for BEV users, to aid in their business model. The insights from this thesis can ultimately raise awareness of the benefits of BEV adoption, and lead to higher BEV adoption rates and the associated benefits of greater BEV adoption across society.

V2H

The analysis gave evidence that access to V2H can have financial benefits to BEV users. The regression estimate for enabling V2H was 0.665 (Table 6-12). It is a significant positive effect on the financial benefits for users. V2H allows the BEV to supplement the residential energy demand by transferring energy to the house, and also allows V2H2G in scenarios where H2G is also enabled. As a reminder, there were no scenarios where V2H was enabled, but H2V was not, given the unreasonable technological setup where transfer of energy from the BEV to the home was possible, but not home to the BEV. Therefore, the net effect of any scenario with V2H should add on the estimate for both V2H and H2V, which in this case is 0.374 (0.665 - 0.291). A hypothesis for the reason for the high benefit is that the BEV is able to import energy from cheaper locations of public charging (i.e., free) and use that to meet the residential energy demand. There is also likely further synergy where H2G is also enabled, allowing the DST to manage the energy use of the BEV to gain income from selling back to the grid at home. Further work in checking the effects of the interactions of V2H and H2G would yield further insight on how beneficial V2H is on its own, and how much added value there is in having both V2H and H2G.

The implications of the results are that having bidirectional energy flow enabled at home alongside a DST can lead to significant financial benefits for BEV users and can be a major attraction for users to own BEVs. Similar possible pathways of attaining the benefits of H2V as mentioned above can be used to attain the benefits of V2H. Government policies can aim to enable V2H for individual users' places of residence and raise awareness of the potential benefits of BEV ownership alongside V2H. Businesses who provide bidirectional energy solutions for residential units can use these findings to alert their customers to the potential benefits.

H2G

The analysis gave evidence that access to H2G can have financial benefits to BEV users. The regression estimate for enabling H2G was 0.244, with a higher benefit of 0.295 for higher H2G income prices, and lower benefit of 0.195 for lower H2G prices (Table 6-12). It is logical that higher H2G income prices lead to higher benefits. The benefits for users would be gained by selling energy at opportune times. This may be from pre-storing energy in the BEV at relative cheaper times to sell back, or from importing energy from cheaper public charging locations. H2G enables revenue generation for users. This is captured as part of benefit and benefit %.

The implication of the results from this analysis is that enabling H2G alongside a DST can be financially beneficial for users. It would be complicated for users themselves to calculate and plan opportune times alongside their BEV charging needs and variations in residential energy prices, thus the DST can enable greater harnessing of the potential offered by H2G. The implications regarding grid balancing potential for TOU tariffs is similarly applicable with the H2G. The added benefit of H2G is that not only can demand during higher stresses on the grid be reduced, but they can also be supplemented by the BEV providing energy back to the grid when the grid is most stressed. The importance of the DST is apparent, as the DST would allow users to naturally aid in providing these services to the grid, as discussed earlier with the TOU tariffs. The potential pathways for attaining these benefits for individuals, energy system, and societal BEV adoption benefits are similar to those discussed with TOU tariffs, as it would be similar policies and business entities who would provide and enable H2G.

A caveat to further analyse would be the original source of the energy which is later sold back to the grid, and the respective effect on the grid stress from public charging, as the element of grid stress during public charging was not considered.

6.2.3.4 *Spatial distribution of the benefits and relationship with spatial welfare levels*

The benefits across all the scenarios were averaged for each borough (Figure 6.14). The spatial distribution of benefits is similar as for Formulation 1, with boroughs south of the river having higher benefits. The discussion for Formulation 1 is referred to (Subsection 0).

A difference for Formulation 2 compared to Formulation 1 is that there are stronger correlations with stronger statistical significance between average benefits of boroughs with the average incomes of boroughs, and with the borough IMD Figure 6.15:

- Income: Formulation 2 -0.451 (p-value 0.0095) vs Formulation 1 -0.334 (p-value 0.0619)
- IMD: Formulation 2 -0.365 (p-value 0.0403) vs Formulation 1 -0.0941 (p-value 0.608)

This gave evidence for two insights. Firstly, that those living in boroughs with lower borough average income and IMD could gain lower financial benefits from optimized energy management of BEVs integrated with residential energy environment. This could lead to exacerbating results for those who are already worse off. The implications are that policies for adoption of BEVs and technologies enabling integration of the BEV with the residential energy environment and the grid should take into consideration each borough's welfare standards if equitable benefits of the adoption of these is desired.

Secondly, by cross-examining the results for Formulations 1 and 2, there is evidence to suggest that with either the access to these BEV integrating technologies, or the wider variety of options available to users, there is a greater degree of differential distribution. The implications are that as the system becomes more complicated to analyse with more variables, there is potential for higher degree of different distribution of the benefits. With the uptake of other technologies also afoot, both related and not related to BEVs and energy systems, careful consideration for equitable adoption of these changes is important.

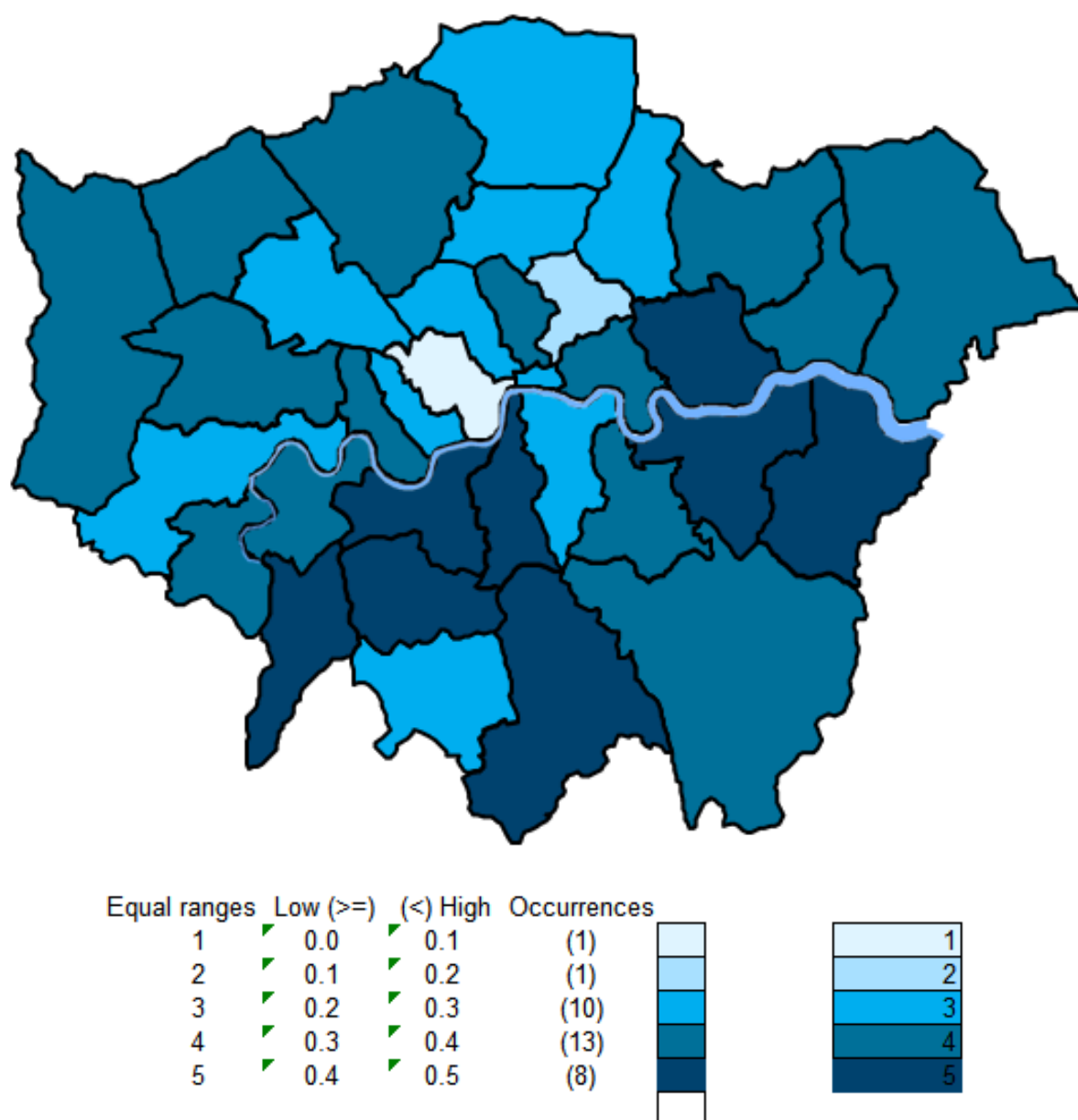


Figure 6.14 Spatial distribution of the benefits for each London borough averaged across all scenarios.

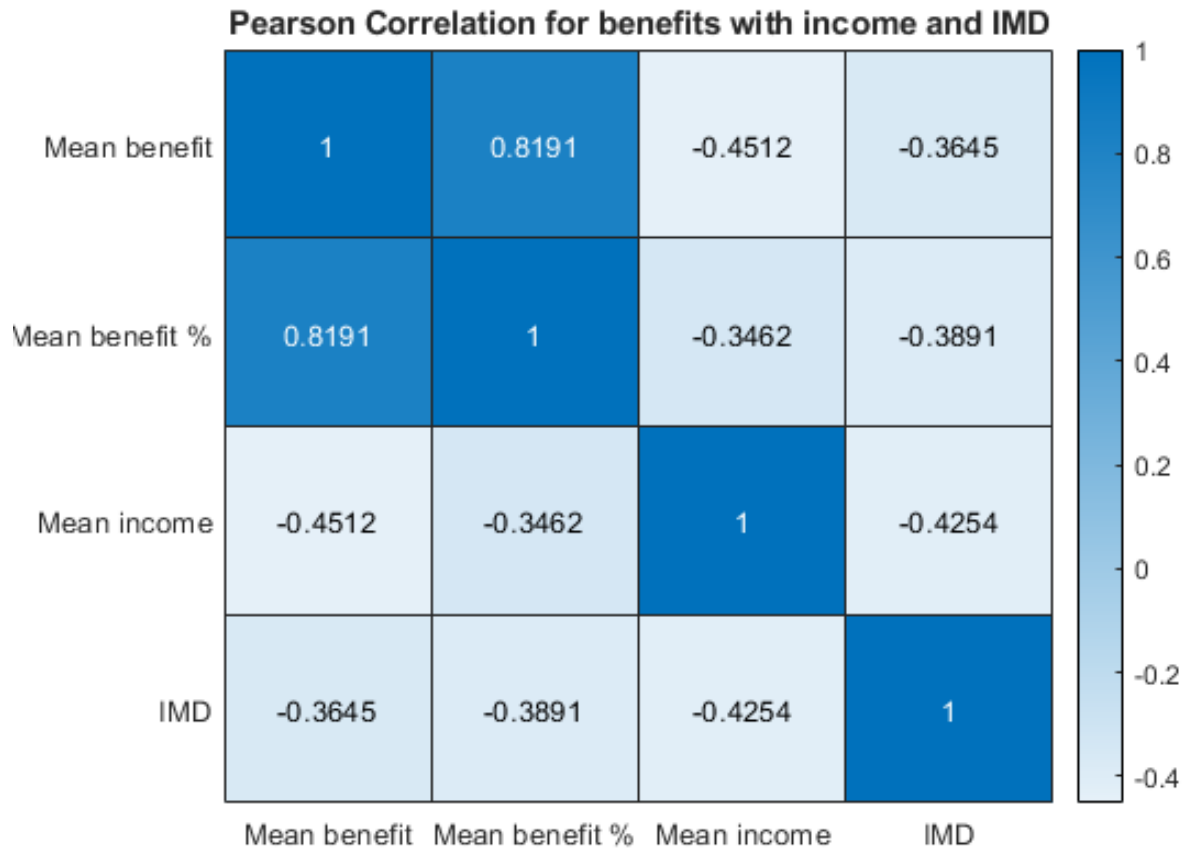


Figure 6.15 Correlation between benefit, borough average income and borough IMD for Formulation 2.

6.2.3.5 Distribution of benefits across demographic characteristics

The analysis of distribution of the benefits across demographic characteristics gave evidence that there is differential distribution of the benefits across different demographics of potential BEV users. The analysis was performed across individuals. The regression estimates are presented on Table 6-13. Results for each of the three demographic characteristics are presented first, then discussion and implications are presented.

Analysis of the regression coefficients for household income categories showed that there was differential distribution across the income levels (Figure 6.16). However, the differences in benefits across the different income groups were not large. The difference between the income group gaining the most and least benefits was £0.108. Similar to the discussion for Formulation 1 (Subsection 6.2.2.3), those with lower household incomes tended to gain less, and those with higher incomes tended to gain more, but those with increasing higher incomes did not necessarily have increasingly higher benefits. The implication is that without careful planning, BEV adoption may exacerbate the inequity in distribution of wealth.

The results for income brackets with their gain from the use of DST are presented in ascending order, relative to the reference category:

- £0-4,999 (reference category): £0.260
- £5,000-9,999: -£0.0458
- £10,000-£14,999: -£0.0339
- £15,000-£19,999: +0
- £20,000+: +£0.0325-£0.0619

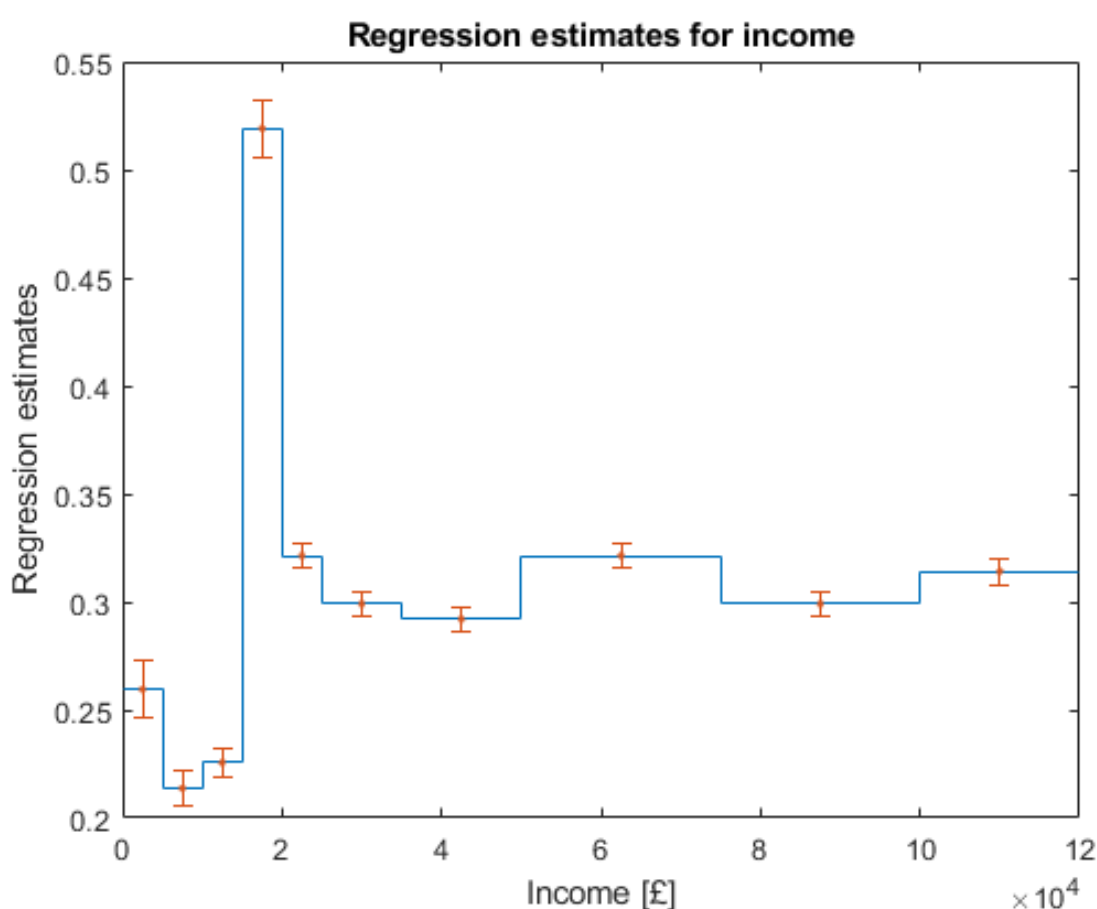


Figure 6.16 Regression coefficients for income with standard errors for Formulation 2.

The analysis for ethnicity showed that there was slightly more segregation of benefits across different ethnicities than in Formulation 1. In Formulation 1, white and black ethnicities gained comparably more but were grouped together, with Asian and mixed forming another group (regression estimate 0.128 and 0.0889 respectively). However, in Formulation 2, those of white, Asian, and black ethnicities had different estimates to the reference of others and mixed ethnicities (0.0562, 0.0788, 0.0667 respectively). This can be seen in Figure 6.17. However, the estimates were lower values than in

Formulation 1. Whilst the absolute values of benefits associated with ethnicities are still not high, the analysis shows there is greater degree of differential distribution. The difference between the ethnicities gaining the most and least benefits was £0.0788.

The results for ethnicities with their gain from the use of DST are presented relative to the reference category:

- Others (reference group: others, mixed): £0.260
- White: +£0.0562
- Asian: +£0.0788
- Black: +£0.0667

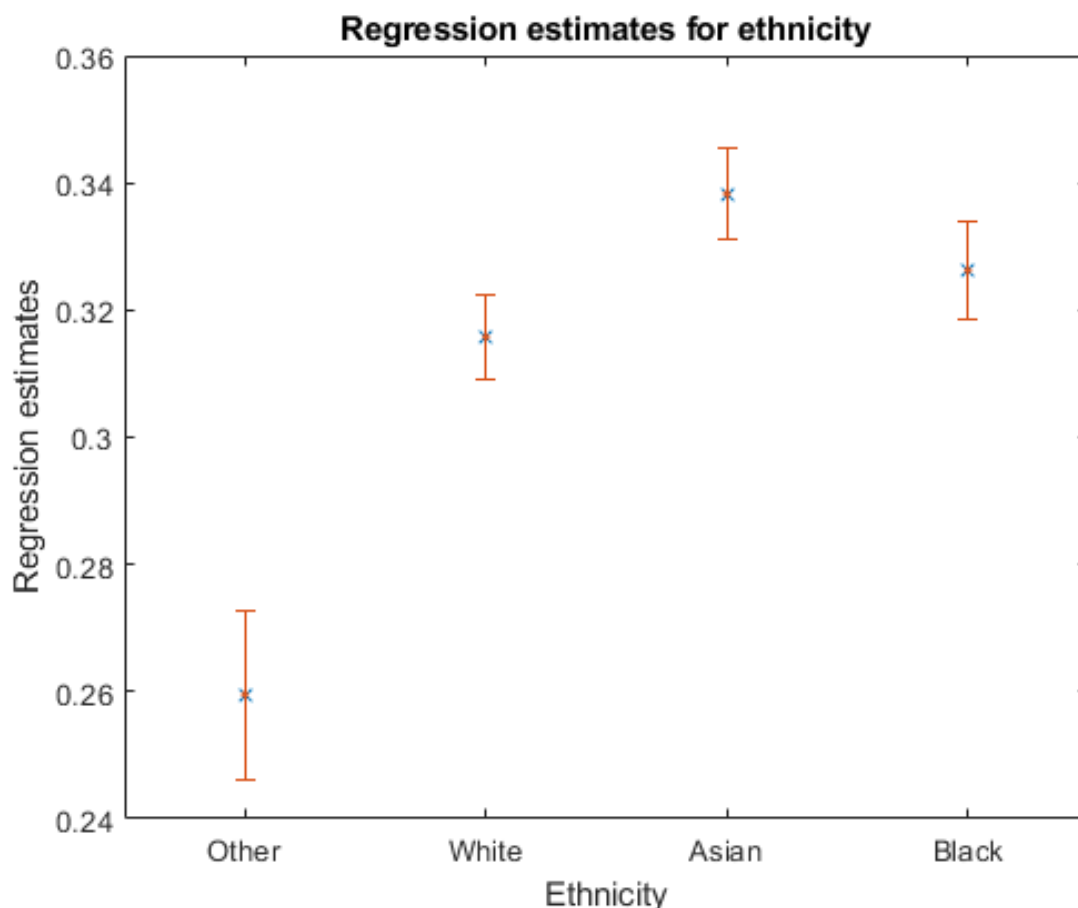


Figure 6.17 Regression coefficients for ethnicities with standard errors for Formulation 2.

The analysis for employment status also showed a higher degree of differential distribution of the benefits compared to Formulation 1. In Formulation 2, relative between users with different employment statuses, those in others category gained the most, then those in full-time employment, followed by those in part-time employment, then students, retired, unemployed, then those looking after home or family. In Formulation 1, the rank was those in full-time, followed by all others jointly,

then retired, then unemployed and looking after family jointly. Analysis of Formulation 2 showed more distinct differences between each employment status. Differences in gains between the demographics were slightly starker for Formulation 2 than 1. A hypothesis is that this is due to the greater number of data points from the larger number scenarios in Formulation 2 than in 1.

The results for ethnicities with their gain from the use of DST are presented relative to the reference category:

- Others (reference group): £0.260
- Full-time: -£0.0533
- Part-time: -£0.118
- Student: -£0.150
- Unemployed: -£0.276
- Retired: -£0.168
- Looking after home or family: -£0.324

Those in full-time gained 0.271 more than those looking after a home or family. Those looking after home or family gained 0.324 more than the reference of others, which represented the groups of highest and lowest benefits. In comparison, the highest and lowest groups for Formulation 1 had a difference of 0.300.

The implications and possible pathways discussed for Formulation 1 regarding the different distribution of the benefits are applicable to Formulation 2 and are referred to (Subsection 6.2.2.3). Furthermore, additional implications can be added from the analysis of Formulation. Mainly, that even greater attention must be given to ensure equitable adoption of BEV when additionally considering the integration technologies with the energy system. That with greater combinations of different technologies available, there is greater potential for disparity between the different demographics in terms of benefits they could gain. This increase in disparity is likely due to the greater variation in the benefits that users could gain depending on the technologies at their disposal. This stresses further importance of the implications, discussions and potential pathways as previously discussed for Formulation 1.

Table 6-13 Regression estimates for demographic variables analysed across benefits of each individual across all scenarios for Formulation 2.

VARIABLES	B	SE	T STAT	P VALUE
Intercept	0.2595	0.01325	19.59	0.0000

HOUSEHOLD INCOME	Reference: 0-4999, 15000-19999				
HOUSEHOLD INCOME	5000-9999	-0.0458	0.00801	-5.72	0.0000
HOUSEHOLD INCOME	10000-14999	-0.0339	0.00667	-5.09	0.0000
HOUSEHOLD INCOME	20000-24999	0.0619	0.00538	11.50	0.0000
HOUSEHOLD INCOME	25000-34999	0.0396	0.00547	7.24	0.0000
HOUSEHOLD INCOME	35000-49999	0.0325	0.00568	5.71	0.0000
HOUSEHOLD INCOME	50000-74999	0.0619	0.00538	11.50	0.0000
HOUSEHOLD INCOME	75000-99999	0.0396	0.00547	7.24	0.0000
HOUSEHOLD INCOME	100000+	0.0546	0.00609	8.96	0.0000
ETHNICITY	Reference: Others				
ETHNICITY	White	0.0562	0.00661	8.51	0.0000
ETHNICITY	Asian	0.0788	0.00717	10.98	0.0000
ETHNICITY	Black	0.0667	0.00775	8.60	0.0000
EMPLOYMENT STATUS	Reference: Others				
EMPLOYMENT STATUS	Full time	-0.0533	0.00927	-5.75	0.0000
EMPLOYMENT STATUS	Part time	-0.1180	0.00984	-12.00	0.0000
EMPLOYMENT STATUS	Student	-0.1503	0.01371	-10.96	0.0000
EMPLOYMENT STATUS	Unemployed,	-0.2763	0.01195	-23.12	0.0000
EMPLOYMENT STATUS	Retired	-0.1677	0.00978	-17.15	0.0000

EMPLOYMENT STATUS	Looking after home/family			
		-0.3243	0.01074	-30.18 0.0000
F vs constant model	RMSE	R ²	Adjusted R ²	
2750	0.946	0.169	0.169	

6.2.3.6 Effects of travel pattern characteristics on the extent of benefits

The analysis gave evidence that BEV users with longer travel itineraries (in generic sense of the word, as a summary of the three travel pattern characteristics analysed) can gain higher financial benefits. The analysis was performed across individuals. The regression estimates are presented on Table 6-14. The overall direction of results is similar to those discussed for Formulation 1 (Subsection 6.2.2.4). Longer travel itineraries i.e., increasing number of stays, total driving distance of the travel itinerary, and average duration of each stay led to greater financial benefits for the users. Given the similarity of results, refer to the analysis, discussion, and implications for Formulation 1.

Table 6-14 Regression estimates for travel pattern variables analysed across benefits of each individual across all scenarios for Formulation 2.

	VARIABLES	B	SE	T STAT	P VALUE
	Intercept	-0.6075	0.00777	-78.19	0.0000
NUMBER OF STAYS	Reference: 0-2				
NUMBER OF STAYS	3	0.3317	0.00828	40.06	0.0000
NUMBER OF STAYS	4	0.4339	0.00901	48.15	0.0000
NUMBER OF STAYS	5	0.5698	0.00899	63.39	0.0000
NUMBER OF STAYS	6	0.6145	0.01007	61.04	0.0000
NUMBER OF STAYS	7-9	0.6524	0.00983	66.40	0.0000
NUMBER OF STAYS	9-16	0.7519	0.01180	63.70	0.0000
TOTAL DISTANCE	Reference: <10				
TOTAL DISTANCE	10-15	0.0766	0.00360	21.27	0.0000
TOTAL DISTANCE	15-20	0.1708	0.00440	38.83	0.0000
TOTAL DISTANCE	20-30	0.2521	0.00409	61.57	0.0000
TOTAL DISTANCE	30-40	0.4230	0.00563	75.11	0.0000
TOTAL DISTANCE	40-60	0.6816	0.00589	115.77	0.0000
TOTAL DISTANCE	60-100	0.7617	0.00652	116.83	0.0000
TOTAL DISTANCE	100-200	1.5067	0.00776	194.06	0.0000
TOTAL DISTANCE	200-366.57	3.4933	0.01835	190.36	0.0000

AVERAGE DURATION OF STAY	Reference: <10				
AVERAGE DURATION OF STAY	10-25	0.0529	0.00844	6.26	0.0000
AVERAGE DURATION OF STAY	25-40	0.1147	0.00825	13.90	0.0000
AVERAGE DURATION OF STAY	40-50	0.1775	0.00867	20.48	0.0000
AVERAGE DURATION OF STAY	50-75	0.1632	0.00721	22.64	0.0000
AVERAGE DURATION OF STAY	75-150	0.2071	0.00674	30.75	0.0000
AVERAGE DURATION OF STAY	150-200	0.2594	0.00736	35.26	0.0000
AVERAGE DURATION OF STAY	200-300	0.3009	0.00730	41.21	0.0000
AVERAGE DURATION OF STAY	300-400	0.3509	0.00821	42.73	0.0000
AVERAGE DURATION OF STAY	400-500	0.4783	0.00807	59.30	0.0000
AVERAGE DURATION OF STAY	500-600	0.5693	0.00758	75.15	0.0000
AVERAGE DURATION OF STAY	600-1050	0.4501	0.00790	56.95	0.0000
F vs constant model	RMSE	R ²		Adjusted R ²	
5530	0.841	0.343		0.343	

6.2.3.7 Effects of BEV specifications on the extent of benefits

The effects of BEV capacities on the benefits to individuals was analysed based on the regression analysis performed across scenarios. The regression estimates are as shown above in Table 6-12.

Similar to the results of the effects of BEV capacities on the benefits in Formulation 1 (Subsection 6.2.2.5), higher benefits were gained with higher BEV capacities. However, the effects of BEV capacities are much lower relative to the effects the other scenario parameters. The MG ZS with

capacity of 44.5kWh gained £0.102 more than the reference Hyundai IONIQ with 38.3kWh. The Nissan Leaf with 40kWh capacity gained £0.0512 more than the 38.3kWh model. The 75kWh model, which had a much different fuel economy to the other three models, gained £0.0780 more than the reference.

The discussion of the results for Formulation 1 are applicable to the discussion for Formulation 2 and can be referred back to. Further to the discussion of the results for Formulation 1, given the new aspects added in Formulation 2 i.e., integration with the residential energy environment, there may be further intricacies and synergies. For example, larger BEV capacities may affect the extent of benefits gainable from V2H. Therefore, further analysis on the effects of interaction of BEV capacities with V2H and H2G could yield further insights.

A further implication beyond those mentioned in the discussion for Formulation 1 is that if there are interactions between BEV capacities with H2V and H2G, government policies could be implemented to speed up H2G availability. Businesses selling or leasing BEVs could raise awareness of the fact that purchasing BEVs with larger capacities can lead to higher benefits for users, as an added selling point.

6.2.3.8 Effects of longer optimization time horizons

Longer optimization time horizons led to higher benefits, similarly to Formulation 1. The results follow the same trend of having decreasing increase in benefits with longer time horizon. The discussion for Formulation 1 is referred to (Subsection 6.2.2.6). However, in contrast to Formulation 2, the decrease in increase in benefits is starker. The regression coefficient for 3-day optimization time horizon is 0.292, compared to 0.295 for 5 day time horizon. A hypothesis for the smaller increase in benefits for 5 day compared to 3 day for Formulation 2 is that with the additional components of V2H2G and dynamic pricing involved, the additional benefits of longer optimization time horizon can be captured faster (takes a shorter optimization time horizon to capture).

6.2.3.9 Formulation 2 summary

The new findings for Formulation 2 are summarised here. The key results are summarised below in Table 6-15, then implications follow below the table.

Formulation 2 added in additional components to the integrated energy system. These components were TOU tariffs, H2V, V2H, and H2G. These components all contributed to additional financial benefits for BEV users, and showed the significance a DST can have on the financial benefits for optimized energy management of an integrated energy system involving BEVs.

As in Formulation 1, the quantitative analysis shows some evidence of differential distribution of financial benefits of optimized BEV charging across demographics. Analysis across demographics show

that there was inequity at an individual level, identifying potential indicators of differential distribution of benefits. Compared to Formulation 1, the results show more differential distribution. Furthermore, there was evidence of unequal distribution of the benefits spatially.

Table 6-15 Summary of key results from Formulation 2.

Key finding	Numerical result (per day)
TOU enables DST to advise users to gain higher benefits	+£0.125-0.159
H2V allows all users, with or without a DST, to reduce their charging cost	N/A
V2H allows users to gain much higher benefits	+£0.665
H2G with a DST allows users to gain higher benefits by selling energy back to the grid	+£0.195-0.295
Higher household income individuals gaining higher benefits	+£0.108
White, Asian and black ethnicities gaining higher benefits	+£0.0562-0.0788
Those in full-time employment gaining higher benefits than those looking after home or family	+£0.271
Those with longer, more complex travel itineraries (in terms of number of stays, total travel distance, and average duration of stay) gain higher benefits	+£0.0529-3.49

The implication from the findings is that integration of the BEV with the wider energy system should be encouraged. There are potential benefits for both the individual users, and the wider energy system. The benefits for individuals are in reducing their energy costs. The decreased cost can aid BEV adoption by incentivising non-BEV owners to consider owning one. The potential benefits for the wider society include the environmental benefits through BEV adoption, such as lower urban air pollution. Furthermore, the analysis in this research shows that a DST alongside TOU and/H2G can offer benefits to the wider energy system through grid load balancing. This benefit is attainable as the DST would naturally advise users to use energy or sell to the grid at times of optimal cost. Varying TOU prices implicitly indicate times of stress on the grid. The DST would harness the opportune times of cost and divert energy drawdown away from times of high price i.e., stress. The DST would also direct energy back to the grid via H2G at times of high income i.e., high stress. The insight into potential stimulation of load balancing by users is a key evidence to support the potential of synergy of BEV, DST and TOU for providing benefits to the energy system.

The insights from this research should inform policy planning and businesses in their decision making. Governments could implement policies to speed up adoption of smart meters real-time dynamic half-hourly TOU residential energy tariffs, H2V, V2H and H2G. This could be in the form of incentives for service or energy providers, or individuals who adopt these transitions. Businesses providing or enabling these transitions could raise awareness of these financial benefits to users to make their products more attractive and aid their business models.

6.2.4 Formulation 3 results and discussion

The results and discussions of Formulation 3 are presented in this subsection. The subsection presents several different topics. The discussion is ordered to first present the results and findings of the aggregated results from the formulation. Then the discussions on the elements added in Formulation 3 are presented. Then the discussions on demographics topics are presented. Then the discussions on travel and BEV topics are presented.

The results and discussions in Formulation 1 addresses RQ1, RQ2, and RQ3 (Subsection 2.4).

Similar to Formulation 2 the analysis was split between analysing for individuals and analysing for scenarios. The analyses based on individuals were:

- Distribution of benefits across demographics
- Effects of travel pattern characteristics

The analyses based on scenarios were:

- Effects of optimizing the charging and energy management
- Effects of BESS and PV on the benefits
- Effects of V2G on the benefits
- Spread of benefits using Gini coefficient

In the case of analysis performed on individuals, the 3,260 individuals' respective benefits for each of the 1,324 scenarios from Formulation 144 scenarios from Formulation 2 and the nine scenarios from Formulation 1 were used. The regressors were the appropriate individual characteristics for travel pattern characteristics and demographic characteristics. These regressors were chosen to enable answering research questions. The scenario parameters were included as regressors to account for the effects of those. These scenarios parameters were BEV capacity, H2V, V2H, real-time dynamic TOU, H2G, BESS capacity, PV capacity, PV season, and V2G. Furthermore, the household size of individuals was included, again to control for effects of those.

In the case of analysis performed on the scenarios, the total 1,477 scenarios from formulations 1,2 and 3 were used, with regressors of: BEV capacity, H2V, V2H, real-time dynamic TOU, H2G, BESS capacity, PV capacity, PV season, and V2G. The scenario respective average benefits of all individuals across all scenarios were regressed using the regressors.

6.2.4.1 *Effects of optimizing the charging scheduling on aggregated results across all scenarios up to Formulation 3*

Across all scenarios, on average compared to the baseline, an individual BEV user gained £1.17 per 1 day of travel itinerary compared to the baseline “dumb charging”. Multiplying by 365 days gives £425. The mean reduction in energy cost due to optimising the charging schedule and energy management to the user of the BEV and residential energy needs was 428%, meaning 100% savings with an additional 328% of the baseline cost as income. The mean baseline cost was £1.02 per day. The mean optimized charging cost was -£0.147; an income of £0.147. These results show the benefits of users using a DST for their BEV and residential energy management decision making. These values give an insight to how much an average London user could gain. The average benefits for Formulation 3 are higher than for Formulations 2 and 1. This suggests that the benefits from the added components for Formulation 3 has potential for greater benefits.

Table 6-16 shows the regression estimates for scenario parameters analysed across average benefits across all scenarios. Access to BESS, PV and V2G have a positive effect on the benefits, and these positive effects are evidenced. These will be further discussed in the subsequent subsections.

Table 6-16 Regression coefficients of scenario parameters analysed for the different scenarios for Formulation 3.

	VARIABLES	B	SE	T STAT	P VALUE
	Intercept	-0.7439	0.05087	-14.63	0.0000
BEV CAPACITY	Reference: 38.3				
BEV CAPACITY	40	-0.0192	0.04943	-0.39	0.6979
BEV CAPACITY	44.5	0.1021	0.06176	1.65	0.0985
BEV CAPACITY	75	0.1134	0.06003	1.89	0.0591
NUMBER OF DAYS	Reference: 1				
NUMBER OF DAYS	3	0.8405	0.27086	3.10	0.0020

NUMBER OF DAYS	5	0.4810	0.07369	6.53	0.0000
H2V	Reference: no				
H2V	Yes	-0.1052	0.01750	-6.01	0.0000
V2H	Reference: no				
V2H	Yes	0.5949	0.01705	34.89	0.0000
RESIDENTIAL ENERGY PRICE	Reference: one price tariff				
RESIDENTIAL ENERGY PRICE	Dynamic TOU average	0.3034	0.01982	15.31	0.0000
RESIDENTIAL ENERGY PRICE	Dynamic TOU low	0.3502	0.01995	17.56	0.0000
RESIDENTIAL ENERGY PRICE	Dynamic TOU high	0.3651	0.01995	18.31	0.0000
H2G PRICE	Reference: no H2G				
H2G PRICE	H2G average price	0.5398	0.01977	27.31	0.0000
H2G PRICE	H2G high price	0.6180	0.01989	31.07	0.0000
H2G PRICE	H2G low price	0.4442	0.01989	22.33	0.0000
PV SEASON	Reference: winter				
PV SEASON	Summer	0.5120	0.01584	32.33	0.0000
PV CAPACITY	Reference: 0, no PV				
PV CAPACITY	0.3kW	0.3653	0.02480	14.73	0.0000
PV CAPACITY	1kW	0.5998	0.02480	24.18	0.0000
PV CAPACITY	3kW	1.1050	0.02461	44.91	0.0000
PV CAPACITY	15kW	3.5909	0.12869	27.90	0.0000
BESS CAPACITY	Reference: 0, no BESS				
BESS CAPACITY	5kWh	0.2749	0.02068	13.30	0.0000
BESS CAPACITY	10kWh	0.3623	0.02068	17.52	0.0000
BESS CAPACITY	15kWh	0.4164	0.02052	20.30	0.0000
BESS CAPACITY	45kWh	0.6826	0.12849	5.31	0.0000
V2G	Reference: no				
V2G	Yes	1.2731	0.14974	8.50	0.0000
F vs constant model		RMSE	R ²	Adjusted R ²	
441		0.269	0.875	0.873	

6.2.4.2 Effects of BESS and PV on the extent of benefits

The results and analysis of the effects of BESS and PV on the extent of benefits are presented. These analyses were performed across scenarios.

The regression analysis shows that optimized energy management with BESS can have a positive impact on the extent of financial benefits. The regression estimates were on Table 6-16. Higher capacities of BESS had benefits at a diminishing rate. The regression estimates for 5kWh, 10kWh, 15kWh, and 45kWh BESS were 0.275, 0.362, 0.416 and 0.682 respectively (Figure 6.18). The access to BESS provides a significant amount of financial benefits with the mean baseline cost of £1.02. Even the smallest 5kWh BESS tested represents over 25% of the mean baseline cost.

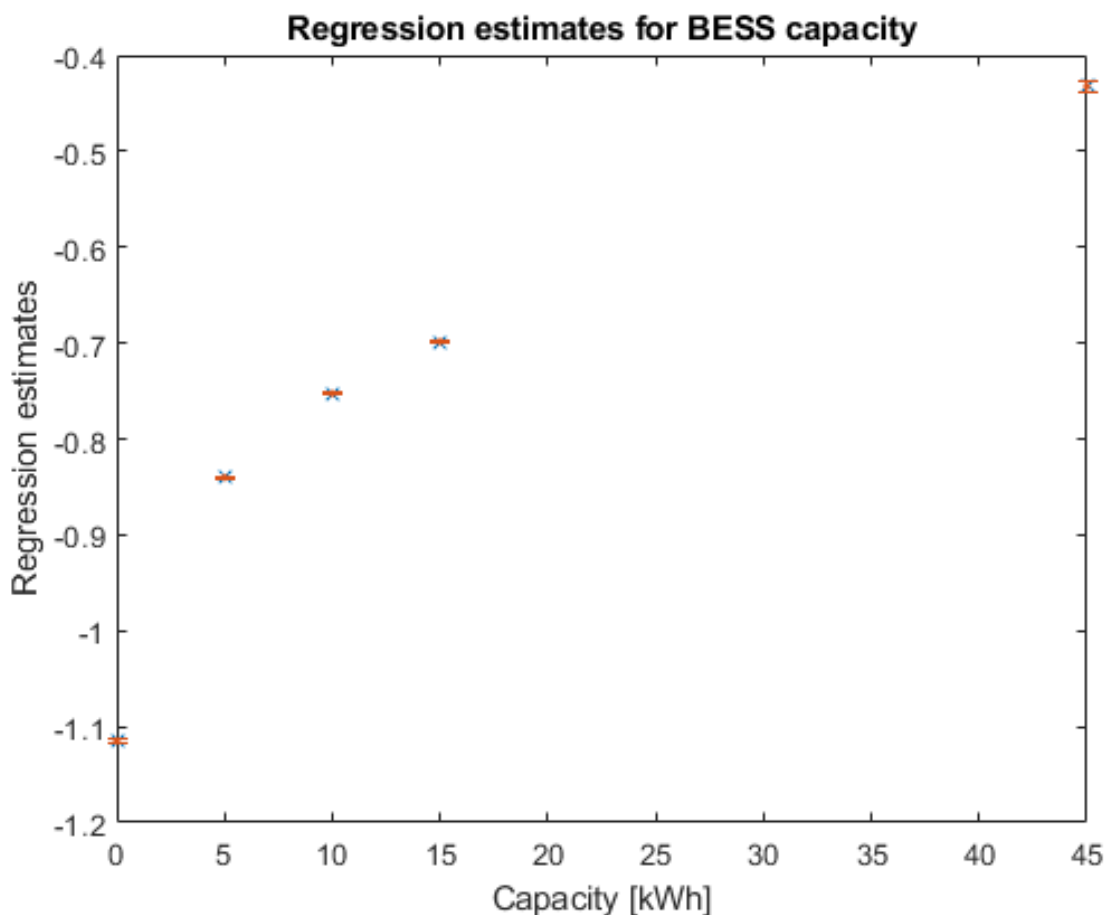


Figure 6.18 Regression estimates for BESS with standard errors for Formulation 3.

The implications of the results and findings are that individual BEV users could benefit financially from having a BESS installed in their home and with optimized energy management. It is possible that with

both a BEV and BESS as storage, the energy management could optimize importing of energy from opportune public charging locations of cheaper price and storing it in the BESS. The storage in the BESS means that even if the BEV's travel itinerary dictates the BEV must leave, the BESS still has the opportunistically gained energy to supplement the residential energy demand. Furthermore, it can be hypothesised that the BESS enables added benefits to the wider energy system as well. The benefits would be from provision of grid services by deferring electricity demand from times of peak stress on the grid. To test this hypothesis, interaction of BESS with H2G could be analysed. As inferred in the discussion for benefits of H2G 6.2.3.3, H2G could be interpreted as a proxy for grid services on the assumption that the price profile of H2G is a proxy for times of stress on the grid. Therefore, analysing the interaction term between H2G and BESS could show how much benefits users could gain, i.e., utilize, the synergy of access to both H2G and BESS.

The regression analysis shows that optimized energy management with PV can have a positive impact on the extent of financial benefits. The regression estimates were on Table 6-16. Higher capacities of PV had benefits at a diminishing rate. The regression estimates for 0.3kW, 1kW, 3kW, and 9kW PV were 0.365, 0.600, 1.11, and 3.59 respectively (Figure 6.19). The access to PV provides a significant amount of financial benefits with the mean baseline cost in mind of £1.02. Even the smallest 0.3kW PV tested represents over 33% of the mean baseline cost. PV enables revenue generation for users when coupled with H2G and/or V2G. This is captured as part of benefit and benefit %.

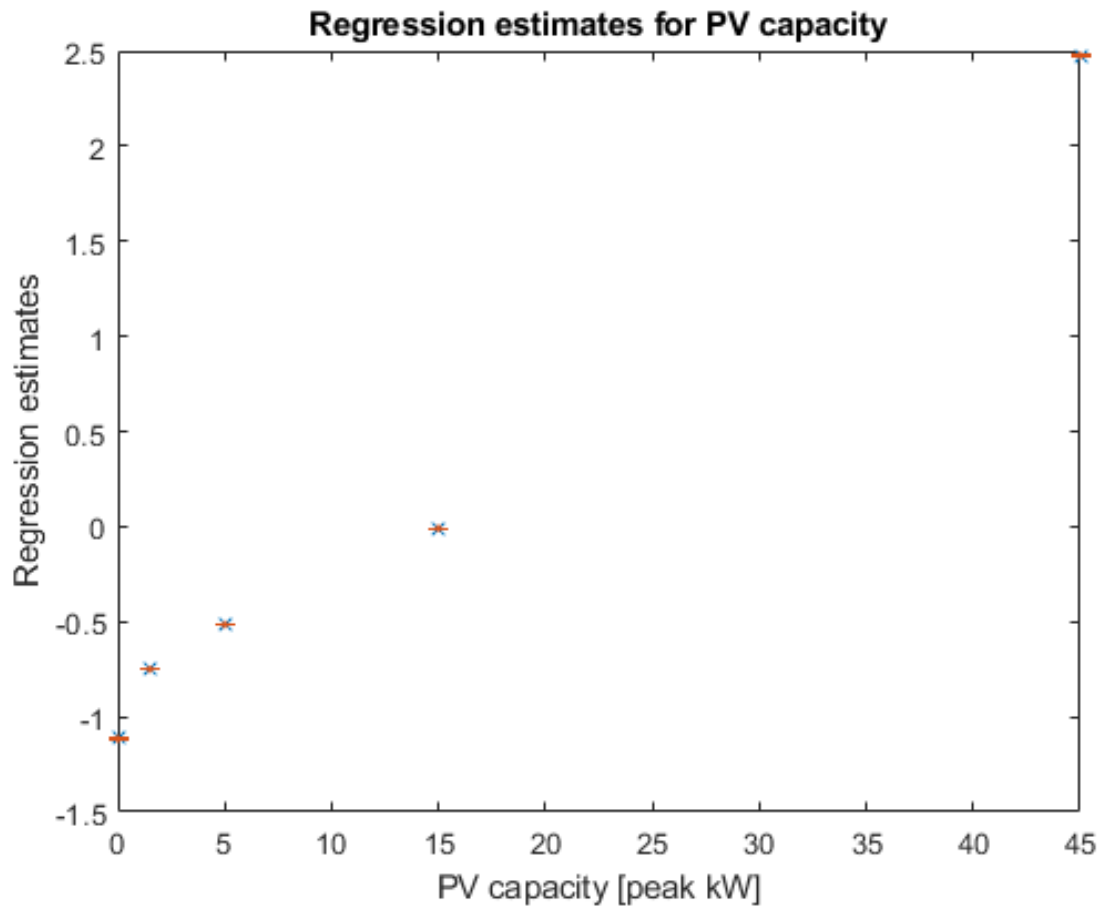


Figure 6.19 Regression estimates for PV with standard errors for Formulation 3.

The implications of the results and findings are that individual BEV users could benefit financially from having a PV installed in their home and with optimized energy management. The benefits may be possible from the BEV providing a storage outlet for PV generation when PV output exceeds residential energy demand. Or even if the PV generation does not exceed residential energy demand, the energy management would use the BEV (and BESS in scenarios with both BESS and PV) to store energy during times of high TOU prices. This would mean the energy management would choose to purchase energy from the grid when it is cheap, even if surplus energy was available, and enabling decreased purchase of energy when prices are high. Furthermore, it can be hypothesised that the PV enables added benefits to the wider energy system as well. The benefits would be from decreasing demand on the grid as the PV would supplement the overall energy demands from the grid. Furthermore, there would be benefits to society of the PV replacing more polluting sources of energy, such as coal or gas.

To attain these benefits from BESS and PV for both individuals and the wider energy network, governments could implement policies to speed up adoption of BESS and PV for households. These could range from raising awareness of the financial benefits for individuals, to financially incentivising

the purchasing and usage of BESS and PV. Businesses that sell BESS and PV could similarly aim to raise awareness and market the financial savings possible for individuals. In the end, as the individuals may be most enticed by the financial benefits they could gain, raising awareness of the savings possible for them could be the most viable and attractive path to faster adoption.

The implications of the findings of this research for governments and energy infrastructure businesses is that stress on the energy system may be decreased, and this may defer necessitating investment into the energy infrastructure system. The country as a whole would produce excess GHG, which would contribute to aims of reaching net zero by 2050. Furthermore, the operating costs of the energy system may be decreased. The benefit for businesses selling or supplying BESS and PV is that the findings could aid in making the market for BESS and PV larger.

6.2.4.3 Effects of V2G on the extent of benefits

The results and analysis of the effects of V2G on the extent of benefits are presented. The analysis was performed across scenarios. The regression analysis shows that optimized energy management with V2G can have a positive impact on the extent of financial benefits. The regression estimate was 1.27 (Table 6-16). The access to V2G provides a significant amount of financial benefits with the mean baseline cost in mind of £1.02. In fact, V2G had a much higher regression estimate than H2G. This is interesting since the prices of V2G and H2G were set the same.

As discussed previously in the thesis in various parts, there are still many challenges for V2G to be used in society. Thus, it was mentioned that the analysis and discussion of scenarios involving V2G was much more speculative.

With this in mind, the implications of the results and findings are that individual BEV users could benefit financially from access to V2G in a similar format with H2G. The discussion regarding H2G in Subsection 6.2.3.3 applies to V2G. The individuals would benefit from selling back to the grid as advised by the optimized energy management. V2G enables revenue generation for users. This is captured as part of benefit and benefit %. The grid could gain benefits through some grid services provided by the users. Within these scenarios, as BESS and PV were also available, it is likely there are additional benefits possible from the synergy between V2G, BESS, and PV.

To attain these benefits for both individuals and the wider energy network, there first needs to be greater research into the potential benefits of V2G, and possible ways of enabling uptake of V2G. This research contributes by showcasing the potential financial benefits for individual BEV users of optimized energy management of their BEV and integrated household energy environment.

6.2.4.4 *Spread of benefits using Gini coefficient for wealth inequality*

The Gini coefficient was calculated across all the individuals' financial benefits for each scenario. It shows the degree of inequality or dispersion of the benefits across the individuals for each scenario. The Gini coefficient is a measure of statistical dispersion intended to represent the income inequality or wealth inequality within a nation or any other group of people.

The Gini coefficient varied across the different scenarios (Figure 6.20), showing that there were differing degrees of inequality of the distribution of the financial benefits depending on the scenario in question. As the analysis showed that there are differing degrees of inequality of benefits amongst users, further research into the types of energy system configurations for individuals that lead to greater inequality is important. Through further research, the reasons for greater inequality could be pinpointed, and thus it would be possible to avoid inequality in adoption of the different technologies.

This research contributes by first quantitatively analysing the extent of benefits. Secondly, this quantitative analysis allowed showing that there could be differing degrees of inequality of adoption of the changing energy system and benefits from the optimized use thereof. This research highlights the need to further research this area to avoid inequity.

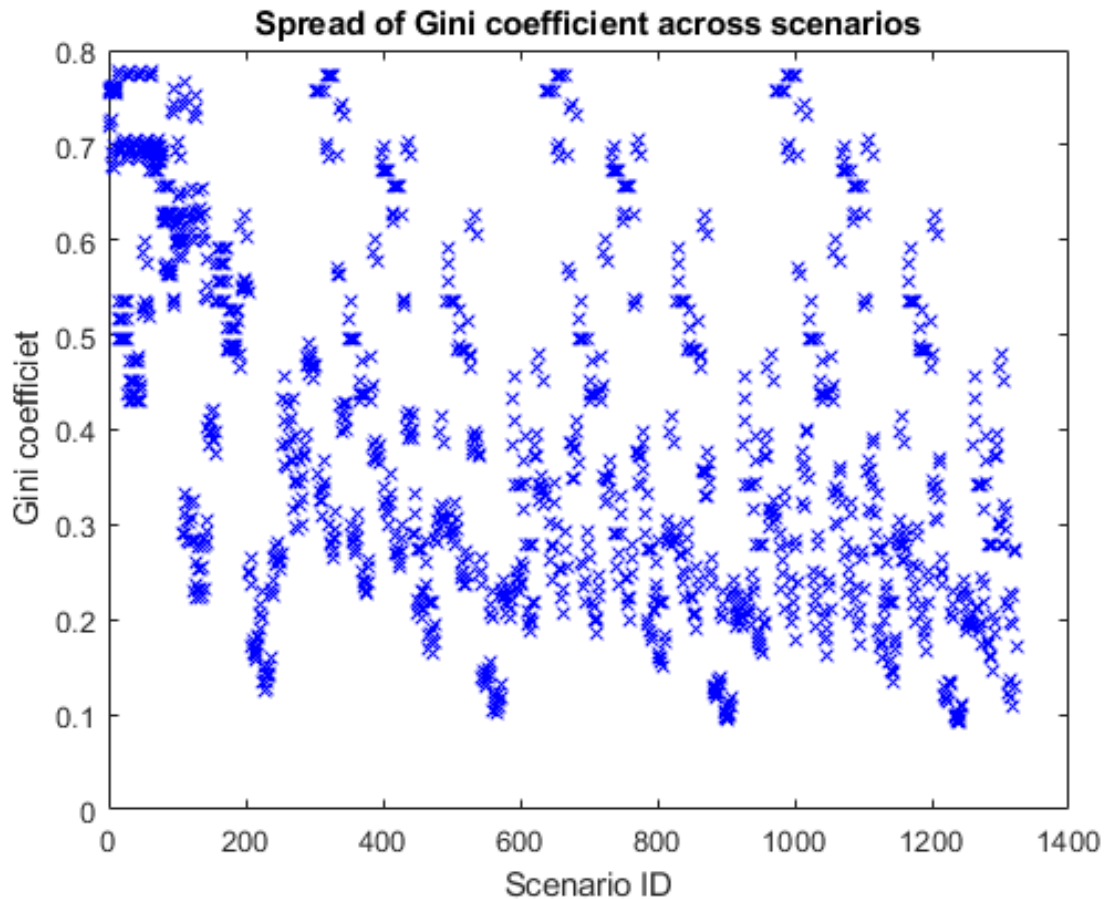


Figure 6.20 Gini coefficient showing the degree of inequality of benefits for each scenario.

6.2.4.5 Spatial distribution of the benefits and relationship with spatial welfare levels

The benefits across all the scenarios were averaged for each borough (Figure 6.21). The spatial distribution of benefits is similar as for Formulations 1 and 2, with boroughs south of the river having higher benefits. The discussion for Formulation 1 is referred to (Subsection 0).

The correlations of the benefits with borough average income and IMD for Formulation 3 have some differences with Formulation 2 (Figure 6.22). The correlation with income was stronger for Formulation 3. The correlation with IMD was weaker, and no longer statistically significant, for Formulation 3:

- Income: Formulation 3 -0.497 (p-value 0.0038) vs Formulation 2 -0.451 (p-value 0.0095)
- IMD: Formulation 3 -0.279 (p-value 0.122) vs Formulation 2 -0.365 (p-value 0.0403)

The discussion regarding the different distribution of benefits across boroughs based on the average wealth and welfare of the boroughs is referred to (6.2.3.4). The results showed that the correlation of benefits with income was very similar between Formulations 3 and 2. However, the correlation with IMD was lower, and no longer statistically significant. This result may suggest that access to BESS and

PV makes the distribution of benefits across boroughs less correlated with the boroughs' welfare levels.

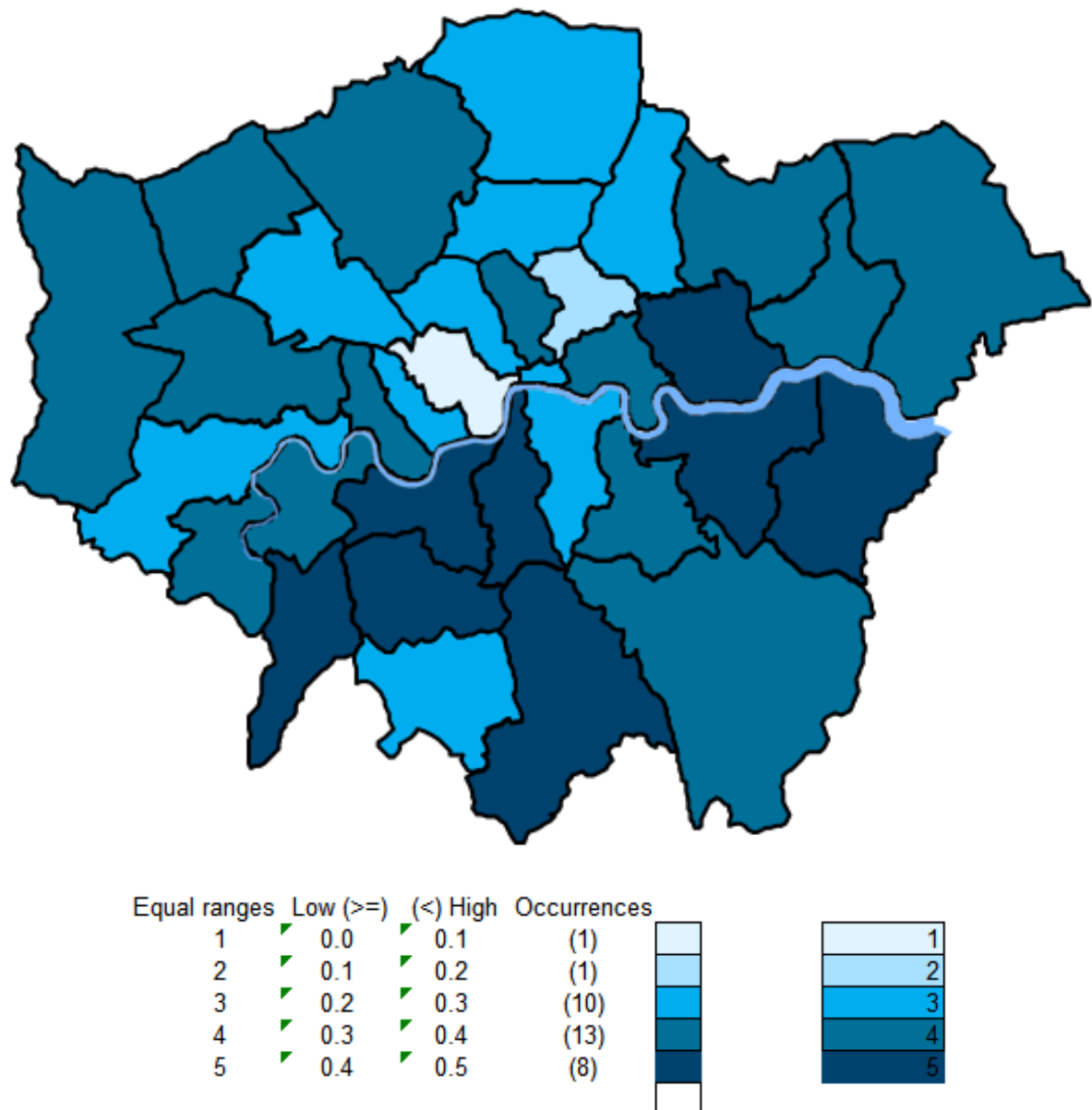


Figure 6.21 Spatial distribution of the benefits for each London borough averaged across all scenarios.

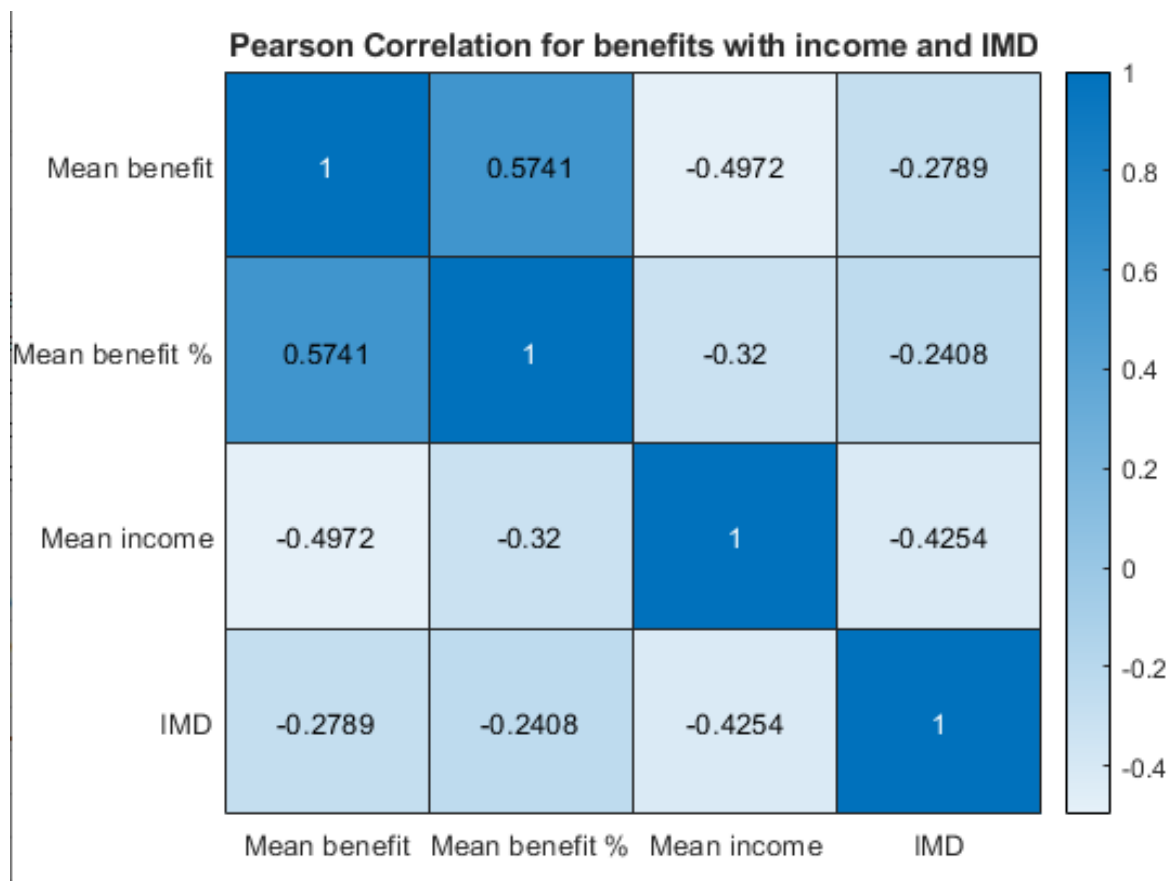


Figure 6.22 Correlation between benefit, borough average income and borough IMD for Formulation 3.

6.2.4.6 Distribution of benefits across demographic characteristics

The analysis of distribution of the benefits across demographic characteristics gave evidence that there is differential distribution of the benefits across different demographics of potential BEV users. The analysis was performed across individuals. The regression estimates are presented on Table 6-17.

Analysis and insights of the regression coefficients for household income categories showed that there was differential distribution across the income levels, ethnicities, and employment. The results were similar to those seen for Formulation 2. Comparison across the three Formulations and a summary are presented in Section 6.3. Those with lower household incomes tended to gain less, and those with higher incomes tended to gain more, but those with increasing higher incomes did not necessarily have increasingly higher benefits. The analysis of the regression estimates for ethnicities and employment status for Formulation 3 yielded similar insights with those from Formulation 2.

Given the similarity of results, the discussion for Formulation 2 is referred to 6.2.3.5, with the specific estimates presented on Table 6-17. The notable differences are discussed here.

There were two differences for regression estimates for Formulation 3 with 2. Asian and Black ethnicities were not statistically different from each. Mixed ethnicities had an estimate that was different to 0 and statistically significant, however, the value was very low at 0.0159, and could be deemed marginal.

For employment status, the ranking of groups that gained the most to least were the same, with some slight differences in the amount gained between them.

Table 6-17 Regression estimates for demographic variables analysed across benefits of each individual across all scenarios for Formulation 3.

	VARIABLES	B	SE	T STAT	P VALUE
HOUSEHOLD INCOME	Intercept	-0.3051	0.00505	-60.42	0.0000
	Reference: 0-4999, 15000-19999				
HOUSEHOLD INCOME	5000-14999	-0.0364	0.00186	-19.63	0.0000
HOUSEHOLD INCOME	20000-24999, 100000+	0.0678	0.00171	39.72	0.0000
HOUSEHOLD INCOME	25000-34999, 75000-99999	0.0441	0.00170	26.01	0.0000
HOUSEHOLD INCOME	35000-49999	0.0360	0.00176	20.48	0.0000
HOUSEHOLD INCOME	50000-74999	0.0732	0.00179	40.96	0.0000
ETHNICITY	Reference: Others				
ETHNICITY	White	0.0671	0.00261	25.68	0.0000
ETHNICITY	Mixed	0.0159	0.00401	3.96	0.0001
ETHNICITY	Asian & Black	0.0776	0.00268	28.99	0.0000
EMPLOYMENT STATUS	Reference: Others				
EMPLOYMENT STATUS	Full time	-0.0319	0.00287	-11.10	0.0000
EMPLOYMENT STATUS	Part time	-0.0958	0.00305	-31.42	0.0000

EMPLOYMENT STATUS	Student	-0.1187	0.00424	-27.96	0.0000
EMPLOYMENT STATUS	Unemployed,	-0.2369	0.00370	-63.96	0.0000
EMPLOYMENT STATUS	Retired	-0.1391	0.00303	-45.89	0.0000
EMPLOYMENT STATUS	Looking after home/family	-0.2855	0.00333	-85.72	0.0000
F vs constant model	RMSE	R ²	Adjusted R ²		
6790	0.91	0.393	0.393		

6.2.4.7 Effects of travel pattern characteristics on the extent of benefits

The analysis gave evidence that BEV users with longer travel itineraries (in generic sense of the word, as a summary of the three travel pattern characteristics analysed) can gain higher financial benefits. The analysis was performed across individuals. The regression estimates are presented on Table 6-18. The overall direction of results is similar to those discussed for Formulations 1 and 2 (Subsection 6.2.2.4). Longer travel itineraries i.e., increasing number of stays, total driving distance of the travel itinerary, and average duration of each stay led to greater financial benefits for the users. Given the similarity of results, refer to the analysis, discussion, and implications for Formulation 1.

Table 6-18 Regression estimates for travel pattern variables analysed across benefits of each individual across all scenarios for Formulation 3.

	VARIABLES	B	SE	T STAT	P VALUE
	Intercept	-1.1150	0.00318	350.57	0.0000
NUMBER OF STAYS	Reference: 0-2				
NUMBER OF STAYS	3	0.3344	0.00253	132.21	0.0000
NUMBER OF STAYS	4	0.4249	0.00275	154.38	0.0000
NUMBER OF STAYS	5	0.5742	0.00275	209.10	0.0000
NUMBER OF STAYS	6	0.6317	0.00307	205.43	0.0000
NUMBER OF STAYS	7-9	0.6648	0.00300	221.49	0.0000
NUMBER OF STAYS	9-16	0.7909	0.00361	219.33	0.0000
TOTAL DISTANCE	Reference: <10				
TOTAL DISTANCE	10-15	0.0740	0.00110	67.23	0.0000

TOTAL DISTANCE	15-20	0.1753	0.00134	130.52	0.0000
TOTAL DISTANCE	20-30	0.2708	0.00125	216.53	0.0000
TOTAL DISTANCE	30-40	0.4515	0.00172	262.45	0.0000
TOTAL DISTANCE	40-60	0.7125	0.00180	396.13	0.0000
TOTAL DISTANCE	60-100	0.8290	0.00199	416.24	0.0000
TOTAL DISTANCE	100-200	1.5865	0.00237	668.87	0.0000
TOTAL DISTANCE	200-366.57	3.4237	0.00561	610.71	0.0000
AVERAGE DURATION OF STAY	Reference: <10				
AVERAGE DURATION OF STAY	10-25	0.0456	0.00258	17.70	0.0000
AVERAGE DURATION OF STAY	25-40	0.1045	0.00252	41.43	0.0000
AVERAGE DURATION OF STAY	40-50	0.1613	0.00265	60.95	0.0000
AVERAGE DURATION OF STAY	50-75	0.1480	0.00220	67.21	0.0000
AVERAGE DURATION OF STAY	75-150	0.1806	0.00206	87.77	0.0000
AVERAGE DURATION OF STAY	150-200	0.2149	0.00225	95.62	0.0000
AVERAGE DURATION OF STAY	200-300	0.2644	0.00223	118.58	0.0000
AVERAGE DURATION OF STAY	300-400	0.3006	0.00251	119.85	0.0000
AVERAGE DURATION OF STAY	400-500	0.4102	0.00246	166.44	0.0000
AVERAGE DURATION OF STAY	500-600	0.4980	0.00231	215.18	0.0000
AVERAGE DURATION OF STAY	600-1050	0.4039	0.00241	167.27	0.0000
F vs constant model	RMSE	R ²	Adjusted R ²		
9660	0.799	0.533	0.533		

6.2.4.8 Effects of BEV specifications on the extent of benefits

The effects of BEV capacities on the benefits to individuals was analysed based on the regression analysis performed across scenarios. The regression estimates were shown above in Table 6-16.

The results for the regression analysis were slightly different to the results from Formulations 1 and 2. However, the values of the estimates were in the similar value ranges of up to 0.1. Different to Formulations 1 and 2, the 40kWh capacity had lower benefits (regression estimate -0.0192) than the 38.3kWh. The regression estimates for 44.5kWh and 75kWh were 0.102 and 0.1134 respectively. In Formulation 2, 44.5kWh had higher benefits. A hypothesis is that with possible synergy of the BEV with BESS and PV having higher capacity BEVs lead to higher benefits.

The discussion of the results for Formulations 1 and 2 are applicable to the discussion for Formulation 3 and can be referred back to. As mentioned in the discussions for Formulation 2, with further components added into the integrated energy system environment (in the case of Formulation 3 BESS and PV), there may be further intricacies and synergies in the system. Therefore, further analysis on the effects of interaction of BEV capacities with BESS and PV could yield further insights.

Further implications beyond those mentioned in the discussions for Formulations 1 and 2 are that if there are interactions between BEV capacities with BESS and PV, government policies could be implemented to speed up BESS and PV adoption. Businesses selling or leasing BEVs could raise awareness of the fact that purchasing BEVs with larger capacities can lead to higher benefits for users, as an added selling point.

6.2.4.9 Effects of longer optimization time horizons

The effects of longer optimization time horizons on the benefits to individuals was analysed based on the regression analysis performed across scenarios. The regression estimates were shown above in Table 6-16.

The analysis shows that the longer day optimization time horizons have higher benefits (Figure 6.23). The regression coefficient for 3 day was 0.841, and for 5 day was 0.481. It is interesting that the regression coefficient for 5 days is lower than 3 days. This may be due to the scenarios in Formulation 3 that are 5 days including special cases. These special cases are the ones with V2G, with large PV (9kW), large BESS (45kWh), with only the Tesla Model Y. This caveat is noted in discussing the results of the analysis.

The discussion, implications, and significance in Subsection 6.2.4.9 are applicable, and is referred to.

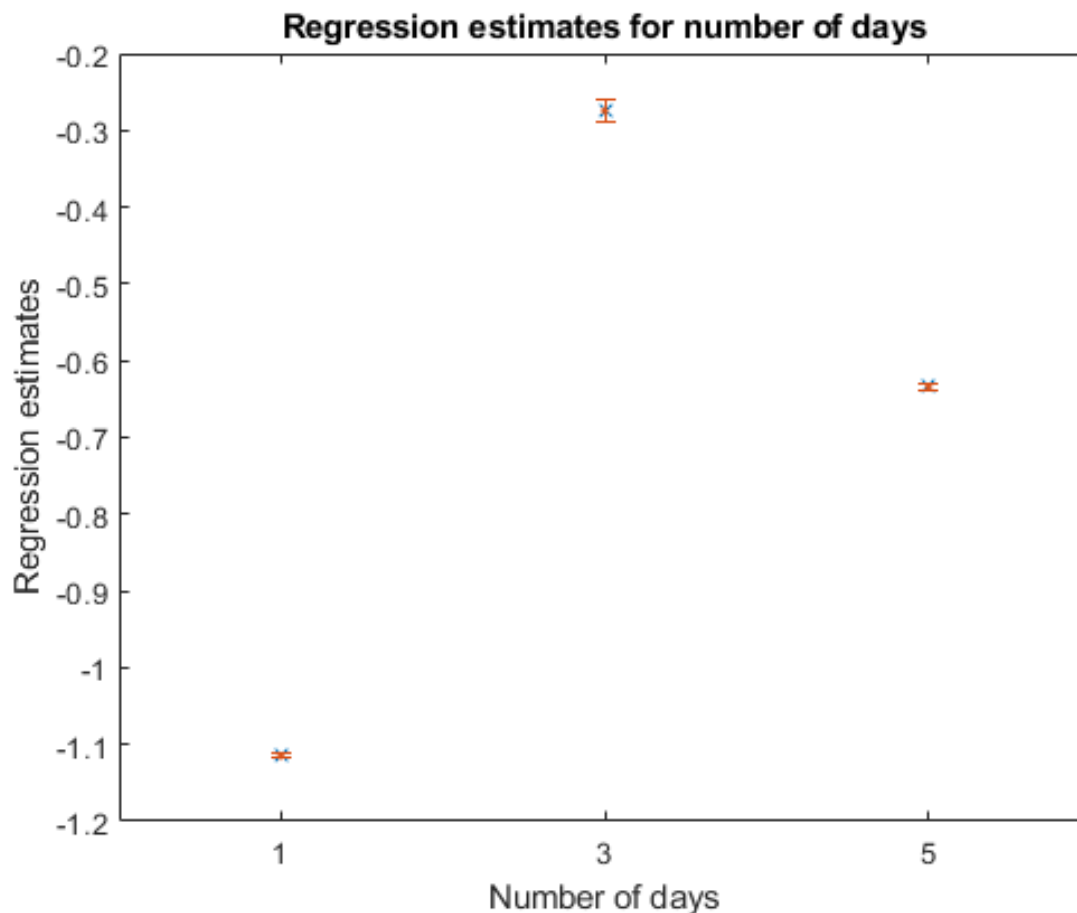


Figure 6.23 Regression estimates for number of days with standard errors for Formulation 3.

6.2.4.10 Formulation 3 summary

The new findings for Formulation 3 are summarised here. The key results are summarised below in Table 6-19, then implications follow below the table.

Formulation 3 added additional components to the integrated energy system. These components were residential BESS, PV, and V2G. These components all contributed to additional financial benefits for BEV users, and showed the significance a DST can have on the financial benefits for optimized energy management of an integrated energy system involving BEVs.

As in Formulation 1 and 2, the quantitative analysis shows some evidence of differential distribution of financial benefits of optimized BEV charging across demographics. Analysis across demographics show that there was inequity at an individual level, identifying potential indicators of differential distribution of benefits. Compared to Formulation 2, the results show more differential distribution. Furthermore, there was evidence of unequal distribution of the benefits spatially.

Table 6-19 Summary of key results from Formulation 3.

Key finding	Numerical result (per day)
BESS alongside DST enables users to gain higher benefits	+£0.274-0.683
PV alongside DST has very high potential for benefits for users	+£0.365-3.60
V2G alongside DST enables users to gain higher benefits	+£1.27
Higher household income individuals gaining higher benefits	+£0.110
Asian and black ethnicities gaining higher benefits	+£0.0776
Those in full-time employment gaining higher benefits than those looking after home or family	+£0.254
Those with longer, more complex travel itineraries (in terms of number of stays, total travel distance, and average duration of stay) gain higher benefits	+£0.161-3.42

The implication from the findings is that adoption of residential BESS and PV, and their integration with the BEV should be encouraged. V2G was stated to require significant work before being available to the public, however, the extent of benefits is showcased in the findings in this thesis. Individual BEV users could benefit financially from having BESS and/or PV installed in their home and with optimized energy management. BESS provides an additional source of storage, which is available even when the BEV is out of home. PV provides a source of energy. Synergy between PV and BEV/BESS is in enabling the capture of excess PV generation, thus increasing utilization of PV generated energy. The BESS or PV or both can then supplement energy to the home or grid if beneficial. The supplementation can also be achieved through V2G indirectly through the BEV as a MES. The supplementation of energy to the home at the right times would have benefits for the wider energy system as it could decrease peak stress on the grid.

The insights from this research can aid in attaining the benefits, and highlights the extent of potential of the benefits attainable. Governments could implement policies to speed up adoption of BESS and PV for households. Faster adoption could be achieved by raising awareness of the financial benefits for individuals, to financially incentivising the purchasing and usage of BESS and PV. Businesses that sell BESS and PV could similarly aim to raise awareness and market the financial savings possible for individuals. The insights from this research points towards the potential benefits of V2G, and further research into the possible pathways to enabling V2G should be undertaken.

6.3 Comparison across formulations

The results found for each of the three formulations are summarised here and compared across the formulations. The changes to the effects on benefits of the different variables as new components are added can be seen. The results are summarised on Table 6-20.

The changes seen across the formulations are discussed here. The overall benefits increase from Formulation 1 to 2 to 3. The reason for that is due to the added components of the system which each contribute. The specific components will be discussed.

In the spatial analysis, there is an increasingly negative correlation between borough average benefit and borough average IMD. This is evidence that differential distribution is a real possibility. Therefore, cross-council coordination accounting for IMD is important when deciding policies and incentives.

Across income and ethnicities, there is a differential distribution, however, the impact is relatively small compared to other factors. There are some differences between formulations, but again, the impacts are relatively small overall. However, governments should be aware of this to ensure equitable distribution of the benefits.

Benefits for different employment statuses had differences across formulations, but the overall trend is consistent; that those in full-time gain more, and those looking after home or family gain less.

The benefits increase for Formulation 3 compared to Formulation 2 for technologies that enable integration between the BEV, home, and grid (H2V, V2H, TOU, H2G). A hypothesis for this is due to the access of PV and BESS in Formulation 3 unlocking further potential. The implication of this is that governments should consider the holistic benefit of synergy between these components, and look to encourage adoption of all technologies. Businesses can use these findings to communicate their value add to consumers.

The benefits across formulations based on the travel pattern characteristics aspects have no identifiable trend, but are always an important factor in the extent of benefits for individuals.

The benefits for longer optimization horizon is highest for Formulation 3, then 2, then 1. A hypothesis for this is that the greater potential of synergy between the components can be harnessed by optimizing further ahead in time, taking advantage of the further complexities in the system. Governments and businesses should raise awareness of the benefits of planning further ahead. The development of DSTs should be promoted.

Table 6-20 Summary and comparison of results for the three formulations.

		Formulation 1 (per day)	Formulation 2 (per day)	Formulation 3 (per day)
Overall	Financial benefits (per year)	£0.541 (regression estimate); £197 per year	£0.627 (regression estimate); £229 per year	£1.16 (regression estimate); £423 per year
Overall	Benefit %	45.8%	222%	428%
Overall	Baseline cost	£1.26	£0.923	£1.02
Spatial	Correlation of benefits with borough average IMD	Not statistically significant (p-value 0.0619)	-0.451 (p-value 0.0095)	-0.497 (p-value 0.0038)
Spatial	Correlation of benefits with borough average income	Not statistically significant (p-value 0.608)	-0.365 (p-value 0.0403)	Not statistically significant (p-value 0.122)
Regression estimate	Reference	£0.210	£0.246	-£0.744
Income	0-£100,000+	-£0.0662 to +£0.0966 (reference=0-4999)	-£0.0458 - +£0.0619 (reference=0-4999)	-£0.0364 - +£0.0732 (reference=0-4999)
Ethnicity	Others, White, Asian, Black, Mixed	£0.0889 to £0.128 (reference = others)	£0.0562 - £0.0788 (reference = others, mixed)	£0.0159 - £0.0776 (reference = others)
Employment status	Full-time, Part-time, Student, Unemployed, Retired, Looking after home/family	-£0.2069 to +£0.0920 (reference = others)	-£0.3243 - £0 (reference = others)	-£0.2855 - £0 (reference = others)

H2V	Yes	N/A	-£0.2906 (reference = no)	-£0.1052 (reference = no)
V2H	Yes	N/A	£0.6650 (reference = no)	£0.5949 (reference = no)
Residential energy price	Dynamic TOU (average, low, high)	N/A	£0.1247 - £0.1590 (reference = no TOU)	£0.3034 - £0.3651 (reference = no TOU)
H2G price	H2G (average, low, high)	N/A	£0.1946 - £0.2951 (reference = no H2G)	£0.4442 - £0.6180 (reference = no H2G)
PV Season	Summer	N/A	N/A	£0.5120 (reference = winter)
PV capacity	0.3-15kW (reference = no)	N/A	N/A	£0.3653 - £3.5909 (reference = no PV)
BESS capacity	5-45kWh (reference = no)	N/A	N/A	£0.2749 - £0.6826 (reference = no BESS)
V2G	Yes	N/A	N/A	£1.2731 (reference = no V2G)
BEV capacity	38.3, 40, 44.5, 75	+£0.0715 - +£0.150 (reference = 38.3)	£0.0512 - £0.1021 (reference = 38.3)	-£0.0192 - £0.1134 (reference = 38.3)
Travel	Number of stays (3-16)	£0.435 - 0.961 (reference = 2)	£0.3317 - £0.7519 (reference = 2)	£0.3344 - £0.7909 (reference = 2)

Travel	Total distance (10-367km)	£0.134 - £4.83 (reference = <10km)	£0.0766 - £3.4933 (reference = <10km)	£0.0740 - £3.4237 (reference = <10km)
Travel	Duration of stay (20-1050mins)	£0.0889 - £0.349 (reference = <20mins)	£0.0529 - 0.4501 (reference = <20mins)	£0.0456 - £0.4039 (reference = <20mins)
Number of days	1, 3, 5	£0.124 - £0.144 (reference = 1)	£0.2923 - £0.2952 (reference = 1)	£0.4810 - £0.8405 (reference = 1)

6.4 Validation

To validate the results of the optimization and regression analysis, the results were compared to studies that analysed energy systems integrating elements of optimized BEV charging, V2H2G, residential BESS and PV. Whilst a like for like comparison was not possible, some isolated effects of different components of the system were compared. A like for like comparison was not possible as these studies had different conceptual frameworks capturing different components or a subset of the combination of the components of the integrated system in this research. Furthermore, these studies had different aims and objectives, meaning the results were based on different performance metrics. These studies provide examples to compare the results with. This enabled validating and comparing the impacts of the addition of different components of an integrated energy system. To present the other studies in a structured manner, two subsections within this section present validating the effects of PV and BESS, and effects of V2G respectively. The results presented in this thesis are compared with those found in the literature. The savings found from the research in this thesis and in the literature are summarised in Table 6-21.

Table 6-21 Summary of effects of BESS, PV, and V2G found in the literature.

Results from this research			
TOU	£0.303-0.365	V2H	£0.595

V2G	£1.27	H2G	£0.444-0.618
PV 0.3-9kW	£0.365-3.59	BESS 5-45kWh	£0.275-0.683
Specific comparison with results from the literature		Results from this research	Results from the literature
PV	3kW vs 1kW with 5 kWh BESS	57.8%	24.5% (Erdinc, 2014)
PV	-	474% (3kW) 257% (1kW)	473% (Wu <i>et al.</i> , 2016)
PV		£0.365-£3.59 reduction (0.3-9kW)	\$2.35 reduction, 40.8% (Duman <i>et al.</i> , 2021)
BESS	Additionally to PV	£0.275-0.683 (5-45kWh)	Additional \$0.72 reduction, 53.3% (Duman <i>et al.</i> , 2021)
TOU	Added benefit from TOU	20.4% with 15kWh BESS and 3kW PV with TOU compared to without	19.6% with 13.5kWh BESS and 3.5kW PV with TOU compared to without (Aguilar-Dominguez, Dunbar and Brown, 2020)
V2H		37.4% with 15kWh BESS and 3kW PV with V2H compared to without	28.6% In presence of BESS (Aguilar-Dominguez, Dunbar and Brown, 2020)
V2G		£463 annual savings	€104-340 annual savings (Salpakari <i>et al.</i> , 2017)

6.4.1 PV & BESS

Erdinc (2014) found cost reduction from PV for households with EV charging to be 31.1%. Having both PV and BESS was found to give cost reduction of 33.7%. Comparing the two results shows the added benefit of BESS to be an additional 8.57%. The capacity of the BEV used in this model was 30kWh. A subset of the sensitivity analysis conducted in the study was extracted to validate the results presented in this thesis. The sensitivity analysis analysed daily cost based on BESS sizes (1kWh, 2kWh, 3kWh, 4kWh, 5kWh) and PV sizes (1kW, 2kW, 3kW, 4kW, 5kW). The results specifically for PV at 1kW

and 3kW for BESS at 5kWh were selected, as these were the same capacities used in this thesis. The result for 1kW PV was 144.9 cents per day, and for 3kW was 109.4 cents per day. The PV of 3kW led to a 24.5% improvement compared to 1kW PV. Compared to the results presented in this thesis, the sum of the regression estimates for 5kWh BESS with 1kW PV or 3kW PV were 0.874 or 1.38 respectively. The improvement offered by the 3kW PV was 57.9%.

Potential financial benefits of smart home microgrids showed benefits of PV (Wu *et al.*, 2016). With PV (winter generation), PEV charging cost changed from \$3.7 to -\$17.5 per day, which is a 473% increase in benefits. The PEV capacity used in the model was 85kWh. The daily energy demand for driving was 12kWh. Compared to the results presented in this thesis, the regression estimates for financial benefit % for PV of 1kW and 3kW were 257% and 474% increases in benefits respectively.

Daily cost comparison of a household and EV without HEMS for with and without PV were \$3.41 and \$5.76 respectively, meaning the PV reduced the cost by \$2.35 or 40.8% (Duman *et al.*, 2021). The results from this thesis were in a similar range, as listed above in the introduction to this section. The daily cost for a system with BESS as well as the PV and EV was \$2.69. The BESS contributed to an additional 53.3% reduction in cost. This was an overall saving of \$3.07. The results from this thesis gave similar savings for BESS. The energy purchased from the grid for the system with EV only, EV and PV, EV, PV and BESS were 40.7kWh, 28.1kWh and 21.5kWh respectively. The same study found for a system with real-time tariff, HEMS and H2G that the daily cost was \$3.91 for EV only, \$0.66 with PV added on, and \$0.1 with BESS added on additionally.

In a household setting with 3.5kW PV system and EV charging demands, the total cost of electricity for various combinations of systems were studied (Aguilar-Dominguez, Dunbar and Brown, 2020). The dimensions which can be compared to the results in this thesis were: residential tariff at flat rate vs time-of-day; V2H vs no V2H; BESS vs no BESS. With a BESS capacity of 13.5kWh. The total costs of electricity for a house with flat tariff without and with BESS were £16.4 and £4.86 respectively. With time-of-day, the costs were £10.3 and £1.63 for without and with the BESS respectively. The costs of electricity at flat tariff without and with V2H were £28.3 and £9.53 respectively. With time-of-day tariff, the costs without and with V2H were £22.1 and £3.25 respectively. From these results, the effects of having BESS, V2H and time-of-day tariff on cost of electricity were isolated:

- TOU: 70.4% reduction with flat tariff; 84.2% reduction with time-of-day tariff
 - I.e., time-of-day tariff improved performance by 19.6% in the presence of BESS
- V2H: 66.3% reduction with flat tariff; 85.3% reduction with time-of-day tariff
 - I.e., V2H improved performance by 28.6% in the presence of BESS
- Time-of-day tariff

- 37.2% reduction without BESS; 66.5% reduction with BESS
- 21.9% reduction without V2H; 65.9% with V2H

The % reduction can be likened to the financial benefit performance metric as defined in this thesis.

The results from this showed that the sum of the regression estimates for the following comparable scenarios were similar:

- With and without TOU at BESS 15kWh with PV 3kW: £1.82 vs £1.52 i.e., 20.0% increase in benefits
 - This can be compared to the 19.6% change as shown in the above study
- With and without V2H at BESS 15kWh with PV 3kW: £2.11 vs £1.52 i.e., 37.4% increase in benefits
 - This can be compared to the 28.6% change as shown in the above study

6.4.2 V2G

An energy management model was presented optimizing smart charging V2G, and space heating load control in a residential microgrid with on-site PV generation (Salpakari *et al.*, 2017). The model included the thermal dynamics of the modelled houses PEVs explicitly, and capacity fade of the PEV batteries. BEV capacity ranged from 16.5kWh to 70kWh. Annual driving mileage was normalised at 18,900km. Energy-efficient space heating and cooling with ground-source heat pumps and ground source free cooling was modelled. The household results were averaged across 10 households in the microgrid. The results showed V2G could achieve €104 to €203 (12–20%) yearly cost savings per household. The yearly savings per household achieved with V2G and space heating load control range from €167 to €340 (19–33%). However, the additional cost savings of V2G compared to smart charging were minor with €4–€8 per household annually (less than 1 %). V2G was found to provide a considerable increase in self-consumption of the locally produced PV electricity, with decrease in bought and sold electricity. The yearly savings possible found from this thesis were £463, assuming multiplication of the daily savings found by 365 days.

6.5 Sensitivity analysis

A sensitivity analysis was performed on the effects on the extents of financial benefits of H2G prices, residential energy prices, and PV generation. The aim was to ascertain how variable the benefits were with changes in prices and PV generation, given that in reality these would fluctuate.

The sensitivity analysis was conducted by analysing the regression coefficients of the scenario parameters of different pricing and PV generation variables. This allowed the analysis of the sensitivity of the effects of these variables on benefits, with all other variables held constant.

The sensitivity analysis was conducted on the following scenario parameters:

- Residential prices: fixed, TOU average, TOU low, TOU high
- H2G prices: average, low, high
- BESS capacity: 5kWh, 10kWh, 15kWh, 45kWh
- PV capacity: 0.3kW, 1kW, 3kW, 9kW
- PV season: summer, winter

Table 6-22 shows the regression coefficients for each of the parameters and their values. For the residential energy prices, H2G prices, and PV seasons, the average prices and PV generation across one day are shown for context. The table also shows the absolute and relative % change for the different values for each parameter compared to the stated scenario to be compared against. The relative % change shows how much the regression coefficients changed as the parameters changed.

Table 6-22 Sensitivity analysis showing the comparison of regression coefficients for the parameters.

<i>Residential energy prices</i>		Fixed: £0.155/kWh	TOU average: £0.135/kWh on average	TOU low: £0.154/kWh on average +14.1% compared to average	TOU high: £0.120/kWh on average -11.1% compared to average
	Regression estimate	0			
	+/-£X		0.3034	0.3502	0.3651
	+/-£X vs TOU average	N/A	0.0000	0.0468	0.0617
	+/-% vs TOU average	N/A	0.00%	15.41%	20.33%
<i>H2G prices</i>		None	Average:	Low:	High:
	+/-£X		£0.0712/kWh on average	£0.0832/kWh on average	£0.0617/kWh on average

BESS capacity			+/-£X	+16.9% compared to average	-13.3% compared to average	
	Regression estimate	0				
	+/-£X		0.5398	0.4422	0.6180	
	+/-£X vs average	N/A	0.0000	-0.0957	0.0782	
	+/-% vs Average	N/A	0.00%	-17.72%	14.48%	
	No BESS	5kWh	10 kWh	15 kWh	45 kWh	
			+100% compared to 5kWh	+200% compared to 5kWh	+800% compared to 5kWh	
	Regression estimate	0				
	+/-£X		0.2749	0.3613	0.4138	0.7559
	+/-£X vs 5kWh	N/A	0.0000	0.0873	0.1415	0.4077
PV capacity	+/-% vs 5kWh	N/A		31.76%	51.46%	148.27%
	No PV	0.3kW	1 kW	3 kW	9 kW	
		+/-£X	+233% compared to 0.3kW	+900% compared to 0.3kW	+2900% compared to 0.3kW	
	Regression estimate	N/A				
	+/-£X		0.3653	0.5976	1.1013	3.6956
	+/-£X vs 0.3kW	N/A	0.0000	0.2345	0.7397	3.2256
	+/-% vs 0.3kW	N/A	0.00%	64.20%	202.51%	883.05%

PV season		Winter	Summer:
		8.31W on	35.3W on
		average	average
			325%
			compared to winter
	Regression estimate +/-£X	0	0.5120
	+/-£X vs summer	0	0.5120
	+/-% vs Summer	0%	N/A

The sensitivity analysis for all the categories tested showed that there was some sensitivity of the extent of financial benefits. The relative change of the benefits for the residential tariff and H2G scenarios were almost +/-20%. The relative changes varied significantly for BESS and PV capacity changes, but not as much as the relative changes in the actual capacities. Whilst the relative changes shouldn't directly mean a likewise relative change in the benefits, the comparison of the relative changes and benefits do show context. The benefits were shown to be sensitive to the variables. This suggests that the results from this analysis may need new analysis for case studies or scenarios where the variables are different. Alternatively, some interpolation could be performed given the fact that this research has contributed by testing wide ranging scenario parameter values. The analysis suggests that individuals' benefits may depend a lot on parameters. Therefore, each person with their own specific parameters would require specific analysis. This makes it harder for individuals to gauge their own benefits. Therefore, it may be harder for users to plan and account for the benefits of adopting these technologies, such as in financial planning. Therefore, this research is impactful as the individuals require their own specific analysis tailored to their situation, and the framework of this thesis allows that.

6.6 Summary of results

This chapter presented the results of the analytical framework based on the conceptual framework. The conceptual framework sought to capture the possible changes foreseen in the energy system. The results presented showed the applicability of the analytical framework analysing the distribution and extent of financial benefits for individual BEV users. This section will summarise the results of this thesis and discuss them alongside the research objectives (Section 1.2), research questions (Section 2.4), and hypotheses and policy questions (Subsection 3.4.1) presented earlier in this thesis.

The order of topic of discussion will be as follows:

- Benefits of DST and optimisation
- Multiday time horizons
- Distribution of benefits across demographics
- Spatial distribution of benefits
- Travel patterns
- TOU
- H2V
- V2G
- H2G
- BESS
- PV
- V2G
- BEV Specifications
- Degrees of inequality (Gini coefficient)

DST and optimization of charging scheduling and energy management of individual BEV users

The results showed that there can be financial benefits for individual users in optimizing their BEV charging schedules and energy management. The analysis of this topic addresses RQ1, Hyp1, and PQ1.

On average, an individual BEV user using the DST could gain £1.41 per 1 day of travel itinerary compared to the baseline “dumb charging”. The mean cost reduction was 416%, meaning 100% savings with an additional 316% of the baseline cost as income. The mean optimized charging cost was -£0.123 i.e., an income of £0.123. The implication of these findings is that the provision and usage of a DST that optimizes the charging scheduling and energy management of an integrated energy system can be financially beneficial for the users, and should be encouraged. In the first instance, the availability of such a DST as a service is necessary and should be researched further. Furthermore, the benefits gained stem not only from just the optimization of the charging schedules, but from the

integration of the different components of the energy system as presented in this thesis. Therefore, the adoption of such components should be encouraged. The implications pertaining to the specific components follow below.

RQ1 and PQ1 are answered. Hyp1 is confirmed. Hyp1: the DST will lower operating cost through optimising the charging decisions. Thus, users will benefit by being aided in their decision making

Multiday

The results showed that optimizing with a longer time horizon of 3 and 5 days (i.e., thinking further into the future gave) gave higher benefits on a per day basis. The analysis of this topic addresses Hyp3.

Optimizing 3 days ahead increased benefits by £0.292 and £0.8405 compared to 1 day in Formulations 2 and 3 respectively. 5-day optimization increased benefits by £0.2952 and £0.481 compared to 1 day in Formulations 2 and 3 respectively. The implication is that users should be encouraged to think further ahead than the immediate next day's itinerary. This has connotations of a shift in mindset amongst society, from short term, immediate needs thinking, to longer term thinking. An example of such shifts outside of the topic of this thesis include demands for reduction in use of single use plastics and packaging. Future studies should consider also optimizing for multiple days when studying charging for individuals.

Hyp3 is confirmed. Hyp3: Longer optimization time horizons will increase the percentage of benefit gained. That is, a time horizon that is twice as long, will have greater than twice the total benefit, and a higher per day benefit.

Demographics

The results showed that there could be differential distribution of the benefits across different demographics in society by household income levels, ethnicity, and employment status. The analysis of this topic addresses RQ3 and PQ5.

Those of lower income, and those not in full time employment were shown to gain less, by up to £0.2855. Not only are they likely to be those already in a worse financial position, but they also have a lower potential gain through optimized BEV charging and energy management. A possible reason for this is those in full-time employment have travel patterns with more potential for optimizing through a DST. The implication of this finding is that if equitable distribution of benefits of BEV and low-carbon transition is desired, carefully and thoroughly informed policies are needed to balance the distribution of benefits. Otherwise, existing inequity within society may be exacerbated by well-intended low carbon transitions. The consequence may be that the poor become poorer, and the rich

become richer. Furthermore, in policy making, greater attention is needed when more technologies are available. The need for greater attention is due to the findings from this thesis which showed greater differential distribution of benefits with a wider variety of technologies available. The insights from this thesis suggest policies should aim to aid wider availability and easier access to BEVs and optimized BEV charging to those who have been found to gain less. Policies' intended affects should be tailored and based on the target demographics' demographic characteristics.

RQ3 and PQ5 are answered.

Spatial

The results showed that there could be differential distribution of the benefits spatially in London. The analysis of this topic addresses RQ3 and PQ5.

The insight from the analysis showed that those in boroughs with lower average incomes could gain lower financial benefits, with a negative correlation of -0.497 between benefits and borough average incomes. The implication is that this could lead to exacerbating results for those who are already worse off. This is due to those who are already worse off gaining less financial benefits from low carbon transition adoption compared to those who are in better financial positions. To mitigate such disparity, policies for low carbon transition technologies should take into consideration the income levels of each spatial area and the extent to which the residents could benefit.

RQ3 and PQ5 are answered.

Travel pattern

The results showed that those with travel itineraries of greater mileage and number of stays gained more, ranging from £0.0457 to £3.42 more. The analysis of this topic addresses RQ1, Hyp2, and PQ4.

The implication is that priority should be given to raising awareness of the benefits of a DST for users with longer travel itineraries. The insight is that the greater benefit may arise from the greater complexity provided by longer travel itineraries, thus giving greater potential to harness opportune charging instances.

RQ1 and PQ4 are answered. Hyp2 is confirmed. Hyp2: There will be a positive relationship between extent of financial benefits and BEV user driving mileage and number of stays.

TOU

The results showed that availability of TOU energy tariffs alongside a DST can have added financial benefits for BEV users. The analysis of this topic addresses Hyp8.

TOU had a regression coefficient of £0.303 - £0.365 (based on pricing scenario) highlighting the high potential benefits of access to TOU alongside a DST. The implication of this research is that the benefits can be for the wider energy system, as well as the individual users. The benefits to the wider energy network stem from the implied load balancing users would provide. This occurs as the DST would naturally advise users to purchase energy from the grid at times of cheaper prices. Times of cheaper prices would be an indication of times of lower stress on the grid. Therefore, energy purchasing from the grid by users at times of higher prices and by proxy higher stress would be avoided. To attain these benefits, governments could implement policies to speed up adoption of smart meters and TOU tariffs. This could be achieved through incentives for energy service providers, or individual users. Businesses providing TOU tariffs could raise awareness of these financial benefits to users to make their products more attractive to consumers.

Hyp8 is confirmed. Hyp8: access to real-time dynamic TOU residential energy tariffs will yield greater benefits as the DST has more opportunities to harness the opportune prices. However, without BESS, the benefits will be less pronounced, as the only access to store the opportune energy prices is through the BEV.

H2V

The results showed that access to H2V could decrease baseline charging cost for all users, with and without the DST. The analysis of this topic addresses RQ2, Hyp6, and PQ2.

There is a significant implication if H2V can decrease the baseline charging cost for all users. The implication is that a significant barrier to BEV adoption could be lowered with access to home charging infrastructure. Home charging through H2V enables users to charge their means of mobility without having to adjust their schedule to make trips for the purpose of fuelling their car, BEV or ICEV. This is made possible as the user is able to charge whilst their BEV is parked at home. The implication from the research is that access to H2V could decrease charging cost for all users. Therefore, users adopting a BEV and H2V home charging would be able to charge their mobility cheaply, and without having to make trips for the purpose of fuelling.

To aid the uptake of H2V home charging, governments could implement policies to subsidise home chargers (some already do). Businesses providing home charger installations can use the insights from this research and spread awareness of the added value of home charging for BEV users. Businesses could also look to acquire or merge with other companies working in relevant, but not overlapping industries and markets. Individuals could be enticed by financial savings they can make through the purchasing of a product or service, and it could be beneficial for a business to raise awareness of this

possibility for their customers. The pathways discussed here that can aid uptake of H2V adoption are similarly applicable for adoption of V2H, H2G, BESS and PV which are discussed below.

RQ2 and PQ2 are addressed. Hyp6 is confirmed. Hyp6: Each of the individual components (access to charging at home through H2V, V2H, H2G) will lead to extra financial benefits for the users beyond those gained by the optimization of charging scheduling only (as in Formulation 1).

V2H

The results showed that access to V2H could decrease charging costs by £0.595. The analysis of this topic addresses RQ2, Hyp6, and PQ2.

Access to V2H had a regression coefficient of £0.595, highlighting the high potential benefits of access to V2H alongside a DST for BEV users. The implications of the results are that bidirectional energy flows between homes and BEVs can be beneficial for users. Furthermore, this research provides evidence of the importance of the role of V2H in integrating an energy system for individuals, and the benefits thereof. For example, without V2G, the ability of the BEV to be utilised as a MES to carry energy from other locations into the BESS would not be possible, nor would the potential benefits for users of doing so. As mentioned above, the pathways to achieving H2V adoption are similarly applicable to V2H adoption. Government policies should aim to enable V2H at residential areas, and raise awareness of the potential financial benefits of BEV usage utilising V2H. Businesses who provide bidirectional energy solutions for residential units could raise awareness to their consumers using these findings.

RQ2 and PQ2 are addressed. Hyp6 is confirmed (written in full above for discussion on H2V). H2G

The results showed that access to H2G could provide financial benefits for users and the wider system. The analysis of this topic addresses RQ2, Hyp6, and Hyp7.

Access to H2G had a regression coefficient of £0.442 - £0.618 (depending on pricing scenario) highlighting the high potential benefits of access to H2G alongside a DST for BEV users. The implication of the findings of this research is that the wider energy system could benefit, as well as individual BEV users. The benefits to the wider energy system stems from BEV users being able to, and financially incentivised to provide grid balancing services to the wider energy network. The underlying reason is similar to as discussed for TOU, specifically, that the DST advises users to sell to the grid at times of higher price, which would indicate times of greater stress for the grid. The importance of a DST is highlighted, as planning selling at high time resolution would be complicated for users. As mentioned above, the pathways to achieving H2V adoption are similarly applicable to H2G adoption.

RQ2 is addressed. Hyp6 and Hyp7 are confirmed. Hyp7: Individuals optimising for their own operating costs can benefit the energy system through provision of grid services (H2G).

BESS

The results showed that access to BESS could provide financial benefits for users. The analysis of this topic addresses RQ2, Hyp9, and PQ3.

Access to BESS had regression coefficients ranging from £0.275 to £0.683 depending on the size of the BESS. This finding highlights the high potential benefits of access to BESS alongside a DST for BEV users. The implication of the findings is that with adoption of BESS, the stress on the energy system could be decreased. This decrease in stress may allow deferring investment into the energy system infrastructure. The stress on the grid could be decreased as BESS provides a source of storage of energy for individual users. Energy stored in the BESS would be utilised at times of higher prices i.e., when the stress is greater on the grid. As mentioned above, the pathways to achieving H2V adoption are similarly applicable to BESS adoption. The implication of the analysis in this thesis is that governments could implement policies to speed up adoption of BESS for households. For example, purchasing and usage of BESS could be financially incentivised. Businesses selling BESS could market the financial savings possible from coupling BESS with BEVs.

RQ2 and PQ3 are addressed. Hyp9 is confirmed. Hyp9: PV and BESS will individually give operational cost benefits to users.

PV

The results showed that access to PV could provide financial benefits for users. The analysis of this topic addresses RQ2, Hyp10, and PQ3.

Access to PV had regression coefficients ranging from £0.365 to £3.59 depending on the size of the PV. The implications of the findings are that there can be benefits for both individual users and for the wider energy system. The benefits for individual users stem from access to a source of energy which can reduce the amount of energy users must purchase but, by supplementing their energy needs. The BEV (and BESS if also used) can act as sources of storage for the PV generation. This adds another element of flexibility which can be optimized, as the PV generated energy can be stored, and used or sold at the most opportune time, based on cost of energy based on TOU, or income from selling back to the grid, again, based on the best price based on the time of selling. The benefits for the wider energy system arise from reducing the demand on the grid. PV would also displace some of the energy generation from other sources which could be more polluting, such as coal or gas. The coupling of PV

with BEV through a DST can contribute to global efforts to reach net zero by 2050. As mentioned above, the pathways to achieving H2V adoption are similarly applicable to PV adoption.

RQ2 and PQ3 are addressed. Hyp10 is confirmed. Hyp10: Individuals optimising for their own operating costs can still have benefits to the system through utilisation of PV (RES), and therefore less stress on the grid, services to the grid through H2G, V2G, and lower grid emissions.

V2G

The results showed that access to PV could provide financial benefits for users. The analysis of this topic addresses RQ2. The analysis and insights are made with the acknowledgement that V2G was seen in the literature to require significant work before being widely accessible to the wider public.

Access to V2G had a regression coefficient of £1.27, highlighting the high potential benefits of access to V2G alongside a DST for BEV users, in a similar manner to the benefits of access to H2G. There could also be benefits to the wider energy system. The grid could gain benefits through grid services provided by the BEV users. The reasoning behind the benefits to grid services provided by BEV users making optimized charging and energy management decisions through a DST are similar as discussed for TOU and H2G, and are referred to. The pathways for adoption for V2G are similar as those discussed for H2G. Added requirements are that further research is needed into the potential benefits of V2G, and ways of enabling the technology for V2G usage.

RQ2 is addressed.

BEV specifications

The results showed that there is no additional benefit from BEVs with higher capacities, but a greater % increase in charging cost is eliminated by the DST. The analysis of this topic addresses Hyp4 and Hyp5.

The implication of the findings is that users do not need to purchase BEVs with larger capacities if their aim is to gain financial benefits. Another implication from the findings is that the DST aids in balancing the potential higher cost of having a higher capacity BEV. Users with higher capacity BEVs were found to incur higher baseline charging costs, and the DST was able to provide proportionately higher benefits, thus maintaining the same % benefit. The insight provided from this research is that there is no additional benefit of having a BEV with higher capacity, but the DST does aid in maintaining the same % benefit by providing the same proportionate benefit.

Hyp4 and Hyp5 are rejected.

Hyp4: There will be little effect of differences in BEV characteristics where the overall mileage of the BEVs stay similar (Nissan Leaf, Hyundai IONIQ, MG ZS).

Hyp5: The higher specification BEV (Tesla Model Y) will yield greater benefits than the others. The increase in benefit can be compared to the increase in BEV purchase cost to compare whether it is financially better in the long term to invest in a more expensive, higher specification BEV.

Gini

The results showed that there are differing degrees of inequality of the distribution of financial benefits depending on the scenarios. The analysis of this topic addresses RQ3.

The implication of the findings from this thesis is that it is important to further research the effects of different energy system configurations on the extent of inequality of distribution of the financial benefits to individual users. It would be important to understand the reasons for the different degrees of inequality of distribution found in this research. Understanding these reasons would aid in avoiding a future inequality.

RQ3 is addressed.

The results and discussions presented in this chapter culminating from the work of this research presented in the earlier chapters of this thesis were presented and summarised.

The conclusions of this thesis will be presented in the next chapter.

Chapter 7

Conclusion

This chapter summarises the motivation and objectives for this research, and the contributions and implications of this thesis, and discusses the limitations and potential future work. Section 7.1 summarises the context of the research, how the research objectives were achieved. Section 7.2 summarises the implications and contributions of this research. Section 7.3 presents possible future work.

7.1 Summary

The motivation for this research stems from the changes afoot in the transportation and energy systems. The adoption of electric vehicles (EV), and specifically battery electric vehicles (BEV), changes the impacts of personal transportation on the energy system, and how the two interact with each other. The adoption of BEVs also creates challenges for BEV users as they must adapt to a completely new way of fuelling their car; a change that society has not had to endure since the introduction of conventional vehicles. The challenges posed stem from the difficulty in processing the large amount of information currently present in a defragmented system of BEV charging. Furthermore, with the increase in amount and speed of information available via internet connections, users must contend with higher resolution data, such as real-time half-hourly dynamic residential energy tariffs.

Whilst there are challenges with BEV adoption, there are also benefits for individual users and for society. Individual users could reduce their charging costs by optimizing their charging scheduling. Benefits for society include reduction in air pollution, and ability to use renewable energy sources rather than fossil fuels to power transportation, and lead to reduction in greenhouse gas emissions.

However, to attain these benefits, the challenges to individual BEV users must be eased. There are further changes in the energy system which compound the complexity of the problem. The compounding comes from the adoption of residential solar panels through photovoltaics (PV), battery energy storage systems (BESS) along with the possibility of integration between the BEV and residential energy system and the grid through vehicle-to-home (V2H), home-to-vehicle (H2V), home-

to-grid (H2G), together vehicle-to-home-to-grid (V2H2G), as well as dynamic residential energy tariffs. This new environment creates opportunities for not only societal benefits, but also financial benefits for individual users such as from lowering their energy cost through harnessing opportunistic times of charging, and use the solar panel generated energy to power their mobility. However, individual users face a challenge in making informed decisions about which technologies they should adopt, which can be most financial beneficial to them, and how to operate within this new environment. Furthermore, there may be inequity in distribution of these benefits across the demographics in society. It is important to research and address these issues prior to these changes being ingrained within society, which can make retrospectively balancing the inequity even more difficult.

The main aim of this research was to explore the benefits, implications thereof, and the equity of distribution to users across demographics, of integrating in a holistic manner an individual BEV user's mobility and energy system environment and optimizing the individual's charging schedule based on their travel itinerary. The integrated energy system environment integrated the BEV, V2H2G, residential energy demand, and residential BESS and PV. To ease these challenges for individual users, a decision support tool (DST) was proposed which combines the charging scheduling of BEVs and integrates with the user's residential energy system.

This exploration could inform important players in BEV adoption, such as governments in policy making, businesses such as suppliers of products, energy providers and charging service providers face challenges adopting the right business model, and in communicating appropriately their business proposition and added value to consumers.

The aim of this research was accomplished by achieving research objectives (RO). The ROs and the tasks (T) necessary to achieve them were outlined in Section 1.2 and are restated below. The contributions of this research were in answering research questions (RQ) (Section 2.4), hypotheses (Hyp), and policy questions (PQ) (Subsection 3.4.1) regarding the extent of benefits to users and society through optimising the scheduling of energy flows between the BEV, grid, home, residential PV, and BESS. The implications and contributions are summarised in Section 7.2. The two ROs were achieved as described below the restated ROs and Ts.

The ROs were:

- RO1: Develop a conceptual framework and DST to navigate the complexity of charging scheduling and energy management within the integrated energy system.
- RO2: Generate insights regarding the extent and distribution across society of the potential financial benefits of optimized energy management for individual users. To gain insights on

how the benefits are affected by the parameters of BEV interactions in an integrated energy system (such as access to H2G, or price of electricity).

The tasks were:

- T1: Develop a conceptual framework for an integrated system of the total energy needs of an individual BEV user. This framework includes the user's travel and residential energy needs and integrates the BEV with the residential home via V2H2G, residential energy demand, BESS, and PV. The travel needs will be based on travel itineraries detailing each trip. The detailing of each trip enables opportunistic charging decision making.
- T2: Develop a decision support tool to assist BEV users navigate the convoluted set of information to consider in making charging scheduling and energy management decisions of the integrated system. Developing the tool is achieved by formulating the optimization problem to minimise an individual BEV user's energy cost of fulfilling their mobility needs with interactions with their integrated energy system.
- T3: Analyse the financial benefits, and implications thereof, to BEV users and distribution across demographics, of an integrated energy system. To achieve this, develop an analytical framework. The analysis is based on the results of the optimization, and the different variables of user characteristics and scenario parameters.
- T4: Provide insights for policy makers and businesses to inform their approaches in adapting to BEV adoption.

To achieve the aims and objectives of this research, RO1 was achieved by completing T1 and T2, and RO2 was achieved by completing T3 and T4.

To achieve RO1, T1 was completed by developing a conceptual framework which represented the integrated energy system environment of individual BEV users. An analytical framework was developed which applied the conceptual framework to assess the extent of financial benefits for individuals operating within such an integrated energy system. These were presented in Chapter 3. Quantifying the extent of financial benefits was achieved by creating and solving the optimizations for the different formulations and scenarios which represent the possible real-world access of different technologies and was presented in Chapter 4; this completed T2.

To achieve RO2, T3 was completed by solving the optimization, using London as the case study as outlined in Chapter 5. The results from the optimization were analysed using regression analysis, and the results, insights, implications, and significance of the research were presented in Chapter 6, completing T4 and addressing the RQs, Hyps, and PQs.

7.2 Implications and contributions of the research

The implications and contributions of the research are summarised in this section. The implications can be categorised in those pertaining to three different categories, and will be discussed in order:

- Benefits for users and the wider energy system
- Inequity of distribution
- Integration of BEVs with the energy system for individuals (V2H2G, BESS, PV)

7.2.1 Benefits for users and the wider energy system

The implication of the research is that BEV adoption and the usage of a DST that optimizes the charging scheduling and energy management of an integrated energy system should be encouraged, as it can benefit individual users as well as the wider energy system.

Benefits for the users were in reducing their ease of operating, and by providing financial benefits. On average, an individual BEV user using the DST could gain £1.16 per 1-day of travel itinerary compared to the baseline “dumb charging”. The mean cost reduction was 428%, which translates to an income of 3.28 times the baseline cost. The mean optimized charging cost was -£0.147 per day i.e., an income of £0.147.

Benefits for the system were through provision of grid balancing services by BEV users. This stemmed from the implicit grid balancing users provided by optimizing for charging costs. Times of higher costs of energy purchase would indicate times of higher stress on the grid. The DST would schedule the charging to take place during times of lower cost, thereby displacing the demand away from times of stress. Lowering the stress on the grid could allow deferring of investment into the energy infrastructure, freeing up budgets for the government. Greenhouse gas emissions could be lowered through the usage of PV generated energy for BEV and residential energy use, which would displace some sources of energy generation which would have higher emissions, such as gas.

Possible pathways of achieving these benefits are through policies that accelerate the adoption of BEV and integration of residential energy systems, as well as businesses in the related industries and markets raising awareness to end consumers of the financial benefits consumers can gain through adoption of these technologies, as evidenced by this research.

7.2.2 Demographics & inequity

The implication of this research is that due consideration must be given to the impacts on equity of distribution of the benefits across different demographics in society of policies driving the adoption of BEV and integrated energy system technologies. The need for giving due consideration stems from the findings of this research which suggest that there could be inequity of distribution of the benefits of optimized usage of BEV and integrated energy systems. Specifically, those with lower income, and those not in full time employment were shown to gain less. Not only are they likely to be those already in a worse financial position, but they also have a lower potential gain through optimized BEV charging and energy management. Existing inequity within society may be exacerbated by well-intended low carbon transitions. The consequence may be that existing inequalities may widen.

The insights from this thesis suggest policies should aim to aid wider availability and easier access to BEVs and optimized BEV charging to those who have been found to gain less. The policies' intended effects should be tailored and based on the target demographics' demographic characteristics. Furthermore, in policy making, greater attention is needed when more technologies are available, as the results showed greater differential distribution of benefits with a wider variety of technologies available.

7.2.3 Integration of BEVs with the energy system for individuals

The implication of the research is that integrating BEVs with V2H2G, residential BESS and PV should be encouraged. This stems from the findings presented in this research which evidence that integration provides greater financial benefits for users, and enables benefits for the wider energy system and society (as mentioned above). Access to TOU tariffs, H2V, V2H, H2G, V2G, residential BESS, and PV were shown to enable greater benefits for users and the system.

Possible pathways of aiding uptake of the technologies enabling integration are similar to those mentioned above regarding policies and businesses raising awareness to consumers. Some governments do already have policies to subsidise the adoption of these technologies, and they could pursue ways of increasing the incentives. Businesses can use the insights from this research and spread awareness of the added value of these technologies for BEV users. Businesses could also work together with synergetic businesses to offer joint products. Businesses could also look to acquire or merge with other companies working in relevant, but not overlapping industries and markets. Individuals could be enticed by financial savings they can make through the purchasing of a product

or service, and it could be beneficial for a business to raise awareness of this possibility for their customers.

A key implication is that policies aimed at accelerating the adoption of these technologies must have given due consideration to the potential impacts of equity of distribution across society of the benefits.

7.3 Future work

The research presented in this thesis makes important contributions, however, there are inevitably limitations and scope for further work. Some of these are briefly discussed here.

Restricting the scope to individually operated vehicles presents potential future research by relaxing the focus on only individual operated vehicles. A potential future research avenue is to include non-individually operated vehicles, such as fleets. The restriction of scope to individually operated vehicles was appropriate as the focus of the research was on distributional effects; individually operated vehicles were the most for the research aims.

The framework presented in this thesis can be adapted to yield results and insights (in terms of financial savings, as well as distributional effects) at a high-level for analysis of fleets. However, for more granular analysis, the framework will need to be adapted at a conceptual level. This is because the current framework evolves around the interactions of an individual vehicle with the operator's household. To appropriately analyse for fleets, the framework will need to be adapted, including changing the focus around household to around a fleet charging facility, or a dispersed charging operating model for the individual charging of fleets. Furthermore, travel data for fleets will need to be obtained. The analysis for fleets will be interesting and insightful as fleets, such as taxis, represent a large number of vehicles on the road in urban areas, and therefore represent a large charging demand, and flexibility options for the grid. The distributional impacts with fleets will require thoughtful conceptual restructuring. This is to appropriately capture the dispersion and representation of individual vehicles within a fleet aggregating to a fleet level. As such, distributional impacts at a fleet level will need defining; the impacts could mean how financial benefits are distributed and affected by fleets operating in different areas, or for different types of journeys.

Further research into the role of commercial buildings and facilities would also yield interesting insights. The research could focus on interactions between BEVs and the grid, and a wider, synergetic energy system, where the buildings could provide a hub for energy interactions. As multiple BEVs would congregate to a commercial building, the building could act as a place of larger scale

interactions with the grid (e.g. V2B). The building could also facilitate a hub for interaction between vehicles, as they provide a place where vehicles could, by proxy of the building, transfer energy between them. Such interactions may be more difficult between houses otherwise.

There were some limitations in the modelling approach taken. Firstly, it was assumed that at each instance of parking there would be a charging point available for the BEV user. Whilst this may be possible in the future depending on the direction of societal and conceptual changes which may go hand in hand with BEV adoption, it would not be the case in the near future. A way to relax this assumption would be to add in a stochastic element to the availability of chargers at each location. Addressing this limitation should be an important consideration for future work.

Another limitation was in treating the travel pattern of BEV users as deterministic. This assumed perfect information from the user and took an approach that could be interpreted as a retrospective analysis of the potential benefits that could have been gained given the specific travel itineraries. This would also be valid in recommending the best course of action for a given schedule. However, analysing the possible actual benefits gained from the usage of a DST would yield some insight, and aid in projecting a plan for the adoption of BEVs and integrated energy systems. A stochastic element to the travel pattern could be applied to gauge how much the users, who may have the intention of a certain travel itinerary, would actually gain with the usage, given that throughout their travel itinerary, they would likely deviate from the initial plan, leading to the DST needing to reoptimize the decisions.

The analysis of the results was performed using linear multivariate regression. This aided in being able to analyse and provide initial insights within the time constraints of the PhD. Future research using more sophisticated analyses would yield more accurate insights and analyses.

Learnings from the thesis is that whilst BEV uptake is increasing as things stand, there is more that can be done to ensure the right support is there in BEV uptake. This research shows that there is financial benefits that can be gained from operating BEVs, which should encourage further BEV expansion. Further encouraging findings for BEV adoption are the synergies possible through interactions with the grid, BESS, and PV. Further research should be undertaken to quantify the distribution of benefits of BEV uptake to ensure equitable adoption. This research suggests that policies should be made tailored to the characteristics of target user groups, as there is potential for inequity in distribution of the financial benefits of BEV adoption. For further impact, it would be important align future work findings with understanding of how policies are made, what metrics policy makers are looking for, and align the findings to those. This would aid increase the impact of research by allowing the results to be directly relatable by policy makers. Furthermore, analysing at the appropriate granularity aligned to policy making granularity would aid in a similar manner. This may involve conducting the analysis

based around the same geographical boundaries in which the policies are made, such as council boundaries, in the UK. Researching specific methods of encouraging BEV uptake was not in scope of the research, given that the aim of the research was primarily on the equity of the distribution of benefits.

Further research into the total cost of ownership and operation of BEVs would be insightful. The results would inform individuals looking to purchase BEVs. Policy makers would be informed in making informed decisions on the financial considerations of uptake of BEVs in society, which would aid in considering the financial incentive policies. An analysis of the total cost of ownership and operation should include cost elements such as fuel, maintenance, insurance, and taxes; the appropriate data would be required. It would be important to consider the pros and cons of including depreciation and net present value into the analysis. Financing methods available to users should also be taken into account. There would be differences geographically in costs such as operations, as well as in taxes. Therefore, it may be more insightful to take select a geographical location as a case study.

Other future work which would yield more insights are discussed briefly. Using multi-day travel itineraries as data, rather than repeating single-day data over multiple days would increase realism. Different scenarios of shares of the BEV fleet of the total personal vehicle fleet could be used in the models. Further V2G scenarios could be analysed to account for the potential of V2G, which is currently seen as still needing much work to make it widely available. Cooperative and competitive behaviour between users could also be researched, to capture, for example, competition for charging between individuals or households. Such interactions could be incorporated into the conceptual framework presented in this thesis capturing the different flows of energy between the BEV, grid, BESS, PV, and household. The interactions could be captured by using the outflow and inflow of energy via the grid as the means of transfer of energy between users. This further research could be achieved by including elements of game theory. Including interactions between users is quite different to the analyses undertaken in this research, and would require thorough further understanding of application of game theory (as an example), to incorporate into the conceptual framework. It is possible that a different analytical framework is required.

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