Electric Vehicle Energy Integration Scenarios: A Feasibility Analysis Environment

by

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"The whole is greater than the sum of its parts"

- Aristotle

ABSTRACT

The UK Government has set a goal that by 2040, every new car will be an ultra-low emission vehicle. This makes the exploitation of excess storage in electric vehicles to provide electricity support potentially beneficial. The technology required to utilise this opportunity is called 'vehicle-to-grid', primarily a vehicle connection post with a built-in bi-directional inverter, providing both vehicle charging and discharging functionality. Through utilisation of this equipment, local energy systems, such as building clusters, can utilise the excess energy stored within the vehicles parked on site.

The aim of this research was to create a platform from which to evaluate the investment opportunity of vehicle-to-grid in a local services case study for future energy scenarios. As such, a feasibility analysis environment was developed that evaluates the economic benefit to both vehicle and building owners in installing vehicle-to-grid. The software has the capability to assess any case study with a collection of buildings, vehicles, photovoltaics or market demand. Energy scenarios have been developed within the software to run case studies for economic evaluation, with the scenarios ranging from building peak shaving, tariff demand reduction, photovoltaic demand shifting and energy market provision. By altering the number of vehicles being assessed, the software can also calculate infrastructure provision requirements and related costs.

Using Manchester Science Park as a case study, the software was evaluated to establish its usefulness in identifying energy support opportunities economically and technically viable to the case study. This was also supported by a verification and validation process to evaluate the software built against original stakeholder requirements. Results showed provision of energy to the capacity market with wholesale market trading was most cost effective compared to the other six scenarios evaluated through the software. A net present value of over £420,000 including infrastructure costs, was calculated after a 10-year intervention using 50 electric vehicle batteries for one hour a day, three days a week with an average energy discharge of 11.5kWh per day.

All but two of the scenarios simulated had a negative saving when infrastructure costs were considered. However, if charging infrastructure were a pre-requisite regardless of vehicle-to-grid provision, the economic case to Manchester Science Park proved to be positive for all but one scenario. One key outcome was the sensitivity surrounding the cost of battery degradation from vehicle-to-grid provision. In four scenarios the simulated degradation cost was too high for the vehicles to make a profit when the cost of re-charging the battery was also considered.

Key Words: *Vehicle-to-Grid, Electric Vehicles, Energy Scenarios, Analysis Environment, Battery Storage, Systems Engineering*

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PRELIMINARY INFORMATION

LIST OF ABBREVIATIONS

ABM	*Agent Based Modelling*
BS	*Battery Storage*
CfD	*Contracts for Difference*
CM	*Capacity Market*
CO_2	*Carbon Dioxide*
CVPP	*Commercial Virtual Power Plant*
DECC	*Department for Energy and Climate Change*
DER	*Distributed Energy Resource*
DoE	*US Department of Energy*
DSM	*Demand Side Management*
DUoS	*Distribution Use of System*
EE	*Element Energy*
EU	*European Union*
EV	*Electric vehicle*
F	*Functional requirement*
FIT	*Feed-in-Tariff*
FFR	*Firm Frequency Response*
GHG	*Green House Gas*
GUI	*Graphical User Interface*
ICE	*Internal Combustion Engine*
IEC	*International Electrotechnical Commission*
IEEE	*Institute of Electrical and Electronics Engineers*
INCOSE	*International Council on Systems Engineering*
IoT	*Internet of Things*
ISO	*International Organization for Standardization*
kW	*Kilowatt*
kWh	*Kilowatt Hour*
MC	*Monte Carlo*
MSP	*Manchester Science Park*
MT	*Mega Tonnes*
NF	*Non-functional requirement*
NG	*National Grid*
NOx	*Nitrogen Oxide*
O	*Operational requirement*
Ofgem	*Office for Gas and Electricity Markets*
OLEV	*Office for Low Emission Vehicles*
PEV	*Plug-in Electric Vehicle*
PHEV	*Plug-in hybrid electric vehicle*
PiM	*Plugged-in Midlands*
PiP	*Plugged-in Places*
PS	*Pumped Hydro Storage*
PSO	*Particle Swarm Optimisation*
PV	*Photovoltaic*
SA	*System Architecture*
SD	*System Dynamics*
SE	*Systems Engineering*
SEH	*Systems Engineering Handbook*
SMMT	*The Society of Motor Manufacturers and Traders*

SO	*System Operator*
SoC	*State of Charge*
SofS	*Security of Supply*
SoI	*System of Interest*
SP	*Science Park*
TOUT	*Time of Use Tariff*
TPM	*Transition Probability Matrix*
TVPP	*Technical Virtual Power Plant*
UK	*United Kingdom*
ULEV	*Ultra-low emission vehicle*
UML	*Unified Modelling Language*
UPS	*Uninterruptible Power Supply*
V&V	*Verification and Validation*
V2G	*Vehicle to Grid*
V2GFAE	*Vehicle-to-Grid Feasibility Analysis Environment*
VPP	*Virtual Power Plant*

NOMENCLATURE

μ	*Mean*
C_{bat}	*Battery capacitance*
C_d	*Battery replacement cost (£)*
C_l	*Labour cost for battery replacement (£)*
DoD	*Depth of discharge (kWh)*
dt	*Over time*
E	*Total battery capacity (kWh)*
e	*Exponential*
F	*Farad (measure of capacitance)*
f	*Function*
L_c	*Battery lifetime in number of cycles*
N	*Number of values*
OCV	*Open circuit voltage (v)*
p	*Probability*
SoC	*State of charge (%)*
SoC0	*Initial state of charge (%)*
t	*Time (time step)*
v	*Voltage (v)*
x	*Observed value*
η	*Efficiency (%)*
π	*Pi*
σ	*Variance*
Σ	*Sum of*
σ^2	*Standard deviation*

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DEFINITIONS

There are a number of terms used within this thesis that require correctly defining in order to understand them in the context of this research.

Vehicle-to-Grid Feasibility Analysis Environment (V2GFAE) – this is the software analysis environment created through this research thesis. It enables users to input case study data (relating to building demand, vehicle usage, PV generation and market information) and evaluate them through six energy scenarios, as described in Chapters 3 to 6.

Stochastic – the methodology used within the V2GFAE to simulate the scenario evaluations and vehicle usage profiles. It refers to a random probability distribution that is then analysed through statistical means to develop a predicted outcome.

Case study – this refers to the system under evaluation within the analysis environment. This could be electric vehicles, buildings, the energy market or a combination of all three. The configuration of the case study is evaluated through the energy scenarios built into the V2GFAE.

Scenario – these are built into the V2GFAE and allow the software user to evaluate the economic viability of the case study for each scenario selected. An output summary identifies whether the scenario produced a positive or negative economic saving.

Use case – this is a systems engineering term and refers to a UML based diagram where each *"Use Case Element represents a users' goal when interacting with the system"* [1].

Class – a collection of objects with very similar roles or tasks within a system [2].

Local Energy System – this refers to the local energy system in which the electric vehicles are evaluated. This includes the buildings, PV, vehicles and charging infrastructure and is referred to as a case study.

Vehicle-to-Grid (V2G) – a system that allows EVs to both charge and discharge the on-board electric vehicle battery using a bi-directional inverter, essentially turning the vehicle into a portable battery storage unit.

Artemis Drive Cycles - these are drive cycles based on statistical analysis of a large number of European real-world driving patterns. They are specified as urban, rural and motorway.

Charge/ Discharge Battery Efficiency – the efficiency of a battery when being charged or discharged. This is usually not 100% due to losses experienced such as a result of heat impact.

CHAPTER ONE

INTRODUCTION

1.1 ENERGY DEMAND IN THE UK

Total UK energy consumption is over 150 million tonnes of oil equivalent per annum and results in around 563.3 million tonnes of carbon dioxide (CO_2) equivalent [3]. Energy supply is the biggest contributor, at over 189.7MtCO_2e and this figure needs to be reduced dramatically over the coming years in order for the UK to reach its CO_2 reduction target of 80% (of the 1990 figure) by 2050 [3][4]. Whilst traditionally power generation has been predominantly fossil fuel based, the UK is diversifying supply to nuclear and renewable sources, with low carbon generation accounting for 35.7% of total UK supply in 2014 [5]. The UK Government low carbon future plans have impacted this shift, along with a reduction in the fossil fuel resources available and increasing gas and coal prices [4]. As such, the source of supply has not only become more complex due to an increase in the number of supply technologies, but an increasing population demands ever higher amounts of electricity.

Electricity demand is set to increase over the next 40 years due to an increasing birth rate, decreased mortality rate, increased immigration and diversification of energy supply to electricity [6][7]. The distribution of demand is also changing, with more people than ever migrating towards large towns or densely populated areas, with the 2011 UK census stating the aggregated UK cities population had increased by 2.5million from 2001 to 2011 [8] [9]. The UK population from the 2011 Census stood at 62.3 million and is expected to increase to 67.2 million by 2020, an average annual growth rate of 0.8% [7]. This correlates closely with the 2014 population projection of 64.60 million [10]. If this is extrapolated, the average UK population can be estimated at 73 million by 2035 and around 82 million by 2050. This represents a population increase of 20 million over 40 years and a corresponding estimated increase in power demand of $\sim$12.62GW per annum during that time. This correlates with the Department of Energy and Climate Change (DECC) reported figure of 58% increase in electricity consumption from 1970-2014, despite decreasing overall energy consumption figures when considering all generation and fuel types [6]. As a result of this growing electricity demand, the UK Government is putting increased pressure on energy consumers to reduce demand, resulting in rising energy bills in the future, partly as due to the impact of energy policies [11]. Predictions indicate an increase in domestic electricity prices by 2030 from 2014 figures, as shown in Figure 1 [11].

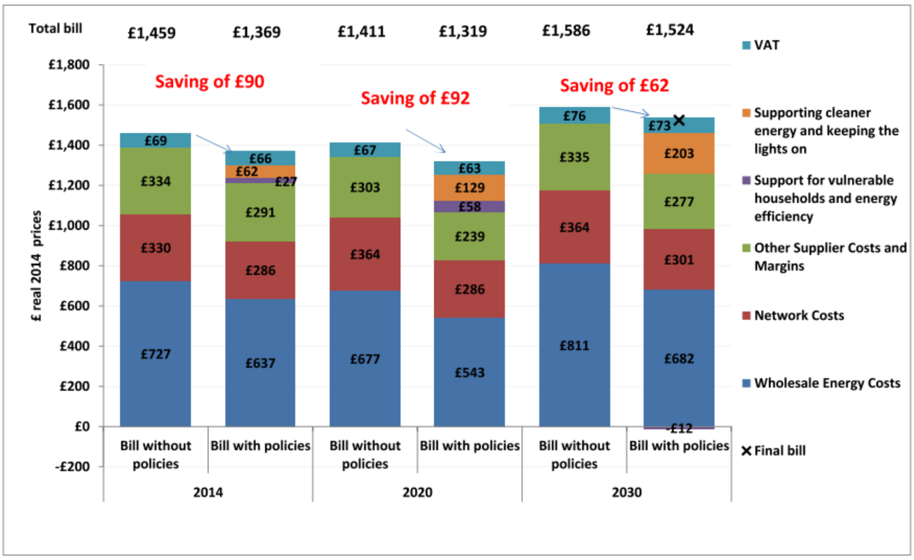


Figure 1 – Projected future electricity and gas price for the services sector [11]

The diversification of previously fossil fuel powered systems to electric, such as heat pumps and electric vehicles (EVs), will put a long-term strain on the UK grid [12]. Transport is playing an increasingly large part in total UK electricity consumption, with EVs projected to contribute up to 60% of total new car sales in the UK by 2030 [13]. This will create extra demand on electricity networks, particularly during peak hours, decreasing security of supply and therefore increasing electricity costs.

1.1.1 UK BUILDING DEMAND

Domestic and commercial electricity consumption had a combined total of 51% of UK demand in 2013, accounting for 191GWh of electricity (Figure 2) [14].

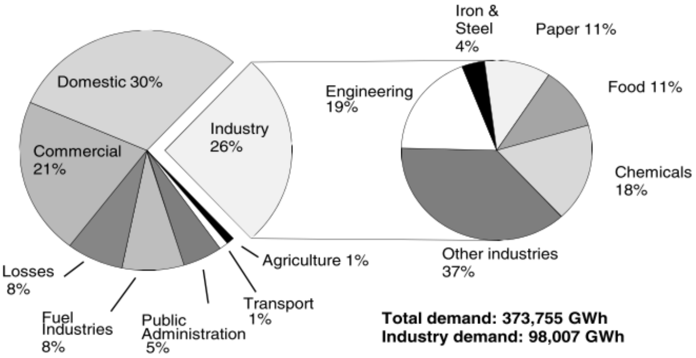


Figure 2 – Electricity Demand by Sector [14]

DECC calculate building energy demand in the UK at 43% of total greenhouse gas emissions (GHG), with commercial sector buildings responsible for 10% of total UK emissions [15][16]. Addressing ways to reduce energy demand in the building sector is therefore essential if the 2050 targets set by

Government are to be achieved. Demand profiles of commercial and domestic sectors vary, with commercial electricity demand peaking during working hours (8am-6pm), whilst domestic demand profiles peak during morning and evening (6-10am and 4-7pm) [17] [18]. Figure 3 indicates the commercial and public demand profile of the UK for a typical winter day in comparison to total UK demand [17].

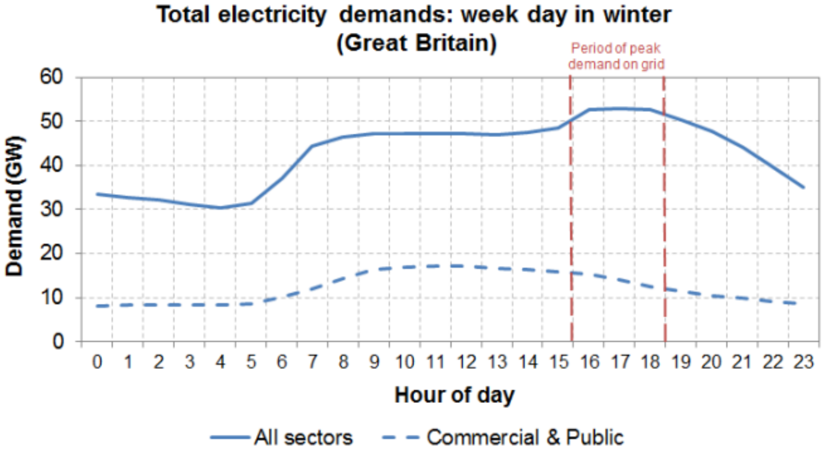


Figure 3 – Typical Winter Day Electricity Demand [17]

1.1.2 The Role of Renewable Generation and Energy Storage

National renewable generation increased by 15% from the 2014 figures to over 20TWh in the first quarter of 2015, demonstrating the significance of renewable technologies in the current UK generation mix [19]. There is a diverse range of the generation types, with bioenergy, hydro, offshore and onshore wind, solar PV, wave and tidal all contributing to UK supply [19]. Photovoltaics (PV) make up the majority of the renewable electricity micro-generation in the UK, with over 682,000 systems under 3kW in size installed by the first quarter of 2015, representing 3550MW of capacity [19]. However, an increasing amount of stochastic renewable generation feeding into the electricity grid increases unpredictability of supply, causing a requirement for increased response services due to the variability of the generation types [20]. In addition, an increasing number of domestic and localised renewable generation technologies create a network less able to cope with the demands placed upon it [20].

There are multiple energy storage types such as; hydrogen, fuel cell, thermal or electrical battery storage (BS). Of interest here is BS, which at building scale can help to offset demand during peak hours and research of BS in combination with renewable generation is widespread [21][22][23][24]. Storage in combination with PV is said to increase the usability of the generation technology, storing excess electricity during the day to re-distribute during peak demand [23]. Parra et al. [23] created a stochastic model of a property with PV, a 10kWh lead-acid battery and 1kW fuel cell. The research predicted that the amount of PV generated on-site would increase with the addition of storage, providing additional income to the occupant through the Feed-in-Tariff (FIT) and reducing the payback period of the storage and PV devices [23]. If FIT were not available, the authors estimated that economic savings could still be made if the property were on a variable rate electricity tariff and storage were utilised during the peak electricity price [23].

Profile smoothing of wind generation is a common application for storage technology, regulating the electricity feed into the grid through providing each turbine or wind farm with storage to regulate provision to the grid [25]. Whilst BS dramatically improves the generation profiles of renewable technology loading onto the grid, a major barrier to wide scale uptake is cost [25]. The potential size and cost of BS solutions is largely dictated by the technology and chemical composition of the cell [24]. Small scale and domestic systems commonly use lithium-ion, vanadium radox flow or flow batteries whilst larger storage systems are often sodium-sulphur [24]. High production costs are associated with lithium-ion and sodium-sulphur due to their high efficiency and power densities [24].

An alternative to using efficient but high cost new batteries is second-life EV batteries [26]. The technology can either be placed into large banks for renewable generation storage, for example at wind farms or for smaller scale domestic and commercial applications [27]. Research has shown this to be an efficient use of second life batteries, however the initial investment costs still present funding issues for smaller scale applications [27]. Whilst utilisation of BS helps with improvements to security of supply, the potential environmental benefits are largely dependent upon the form of energy generation entering the batteries [28]. McKenna et al. [28] created a battery model of static lead-acid batteries operating under a time-shifting scheme to exploit varying electricity tariffs. One of the outcomes from the research identified the negative environmental impact of using the batteries for this operation under the UKs 2013 grid mix [28]. This was largely due to the energy losses encountered with the BS system during charging and discharging of the battery, with losses the equivalent of driving over 4000km (per annum) in an internal combustion engine vehicle when considering the battery whole lifecycle [28]. The research also identified economic losses of ~£1000 per annum for a 570Ah battery combined with a 3.29kW peak PV system [28].

1.1.3 THE POTENTIAL OF VEHICLE-TO-GRID

One opportunity to utilise existing storage assets is operating EVs as an aggregated energy store, providing peak shaving or demand shifting to local buildings or the power system when demand is high. The technology to facilitate this is called vehicle-to-grid (V2G) and is a novel concept to the UK, with only three known systems currently in operation at the time of writing, one at Aston University and two at the University of Birmingham. The USA is more developed in terms of the economic opportunities V2G presents, with a 36 vehicle research trial already in operation, conducted by the United States Air Force [29][30]. Total electricity provision of the trial equals 996kWh, using 34 vehicles with a combination of 50kW and 15kW power capacity ratings [31].

V2G performs similar functions to traditional EV charging infrastructure, charging the vehicle when connected. However, whilst standard charging requires only a uni-directional inverter, V2G contains a bi-directional inverter, allowing energy to flow both to and from the vehicle. The application of bi-directional inverters with EVs is a relatively new one for the UK, despite the interest in North America. Japan has also seen a strong increase in the number of systems available and being developed due to grid insecurity after the Fukushima disaster in 2011 caused widespread power losses across the country [32][33][34]. The UK power system however, is currently much more secure in relation to widespread network outages and therefore reasons for uptake are predominantly related to economics as opposed to grid security. However, general industry consensus indicates reasons for uptake in the UK are predominantly related to economics as opposed to grid security [35].

1.2 PROBLEM STATEMENT

Considering the knowledge base explored in this chapter and in the literature reviewed in Chapter 2, all research evaluated focuses on one primary aim; to assess a particular vehicle data set within a given scenario to evaluate the suitability of V2G based on a variety of criteria. Understanding the relationships between EVs, users, buildings and energy markets is key to evaluating the economic potential of V2G in the UK. The lack of public evaluation into the economic potential for EVs with V2G in a variety of scenarios in the UK provides the primary motivation for this thesis. As such, this research project has been created due to a desire to understand the complex economic relationship between EVs, their users, buildings and energy markets. The primary driver for this research is from the industrial sponsor Cenex, who would like to provide consultancy services for customers whilst also providing solutions to reducing the carbon intensity of customer fleets by promoting alternative technologies, such as V2G.

1.3 RESEARCH AIMS AND OBJECTIVES

The aim of this research is therefore to create a platform from which to evaluate the investment opportunity of V2G in a local services case study for future energy scenarios. This will be facilitated through the creation of a software environment and meeting the following six objectives;

1. Define the requirements for the research project through development of a systems architecture.
2. Identify the use cases for evaluation from the case study.
3. Specify and develop the scenarios for case study evaluation within the software environment.
4. Using the requirements specified for the system architecture and scenarios, develop the software analysis environment.
5. Identify and validate the data for the case study evaluation, using building aggregated electricity demand, vehicle telemetry, PV generation data and energy market demand data.
6. Using Manchester Science Park as a case study, test the software through the built-in local services scenarios and verify and validate against stakeholder requirements.

The investment opportunity will be assessed against two key areas; a) the anticipated local economic savings, such as clusters of buildings through peak shaving, time of use tariff support and PV charging integration; and b) the suitability of EVs with V2G to provide electricity to energy markets such as Short Term Operating Reserve (STOR) and the Capacity Market supported with wholesale market trading. These markets have been identified due to the buy-in and response requirements being suitable for the operational requirements of V2G units, as is discussed in Chapter 2.

It is important to note that the economic comparison of EVs with traditional internal combustion engines (ICEs) is out of scope. This research is seeking to establish if there is an economic benefit to existing or future EV owners signing up to a V2G scheme, or in building owners installing V2G infrastructure to reduce building costs, not to evaluate vehicle total cost of ownership.

1.4 THESIS STRUCTURE

The Engineering Doctorate (EngD) degree is a well-established programme within both academic and industrial circles, with a different set of qualification requirements to a traditional PhD due to an emphasis on finding real-world solutions to problems faced in industry. This EngD was run through the Systems Engineering Doctorate Centre (SEDC) based at Loughborough University and provided four years of industry led study, with the first year entirely given over to the Systems Engineering MSc programme. As a result, the structure of this thesis follows an industry based approach, with a systems engineering methodology to software design, build and testing ensuring the research aim is achieved through a rigorous, industry relevant process. The scope of the research is broad, with particular attention paid to the development and process engineering involved with software development, as would be the case for traditional, industry lead research in the systems engineering domain.

Research initially began with a comprehensive literature review to gain a full appreciation of the context and background of EVs in relation to BS applications. Energy demand in the UK and the role renewable generation and BS has to play in this sector is also assessed, along with current and developing energy markets. The underlying need and development of the EV is evaluated with relation to the perceived environmental benefits of the technology compared to the traditional ICE. An assessment of the current research that looks at EVs in combination with V2G is evaluated in relation to the models already developed in the literature reviewed. This demonstrated a lack of current understanding as to which case studies might potentially be optimal for EVs with V2G. Extensive evaluation of the research space and detailed exploration of modelling approaches for the creation of an analysis platform for V2G electricity support has also been carried out. Through utilisation of a model driven architecture (MDA) approach to the design of a software platform, the Vehicle-To-Grid Feasibility Analysis Environment (V2GFAE) was created. Subsequent testing, validation and verification of the software is then performed, with the research method following the traditional systems engineering (SE) approach, as shown in the SE 'Vee' in Figure 4.

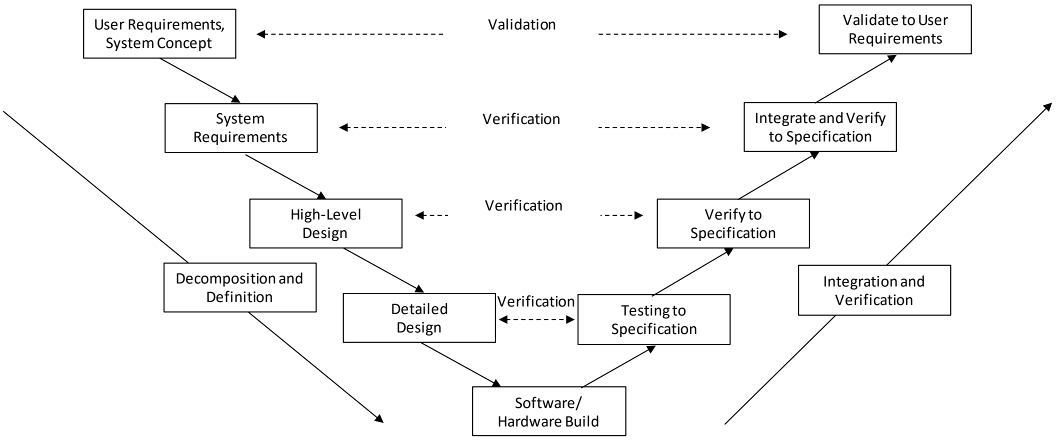


Figure 4 – Systems Engineering 'Vee' (Adapted from [36]*)*

The structure of the thesis therefore closely follows the SE 'Vee' and is presented in the following chapters after this introductory chapter:

Chapter 2: This describes the context of the research through a review of literature and existing models and identifies research gaps.

Chapter 3: This details the systems engineering process undertaken in developing the requirements and system design of the V2GFAE. Initially the chapter discusses the background to the engineering approach taken, before detailing the operational, functional and non-functional requirements of the software through an MDA approach. Appendix A contains the supporting information for the diagrammatical approach to the creation of the software class diagram.

Chapter 4: Development of the V2GFAE is undertaken in this chapter, with a detailed explanation as to the programming approach undertaken. The equations created in this research, (upon which the software is built are given) along with excerpts from the code in which they are implemented. The software is comprised of the following sub-models; vehicle, building, PV, market and cost. Appendix B contains an example of the final output report from the software execution.

Chapter 5: Demonstration of the application for the V2GFAE is given in this chapter, with Manchester Science Park used as a case study. Here the software is used to evaluate the Science Park with relation to EVs with V2G. A variety of scenarios and building case studies are evaluated to fully demonstrate the diverse application of the software.

Chapter 6: An evaluation of the performance and suitability of the software with relation to the original requirements as defined in Chapter 3 is performed. Verification and validation of the software following a SE based approach, as specified in Chapter 3 is performed.

Chapter 7: Conclusions from the research are discussed, along with an evaluation of the research undertaken and an appreciation of its limitations. Suggestions of further work to be done is also identified.

Appendix C lists the journal and conference papers written and presented in support of this thesis.

1.5 NOVELTY OF RESEARCH

This work has been created to assist the author in gaining an understanding of the knowledge space identified as part of this thesis, the process used in creating the V2G analysis environment and the subsequent evaluation of the usefulness of this environment for future planning. The scope of the research is intended to explore the potential for EVs in providing storage and electricity to buildings and selected energy markets. It is acknowledged that whilst other storage technology exists, such as static battery and second life EV batteries, the purpose of this research is to provide a starting point for analysis of existing and potentially underutilised storage assets. Research into this field of study already exists as is discussed in Chapter 2, however development of a software platform for analysis of case studies through multiple energy scenarios is lacking. The novelty of this research thesis stems both from the research outcomes and software developed:

1. Using the software, the research makes informed and logical summations as to the economic benefit of EVs with V2G in select scenarios, using Manchester Science Park as a case study. The complexity of the software makes multiple scenario evaluation possible, unlike the other research evaluated in this field, where single case studies are assessed.
2. The software developed through this project is novel in its approach to problem solving in the energy and vehicles research area. Through utilisation of empirical data, stochastic modelling techniques and logic based algorithms, the V2GFAE software simulates vehicle use profiles, service provision suitability and the associated economic benefit.

Through development of the V2GFAE it is envisaged that the information gained through case study analysis can be used to inform fleets, EV drivers and property owners as to the suitability of a V2G energy solution. Cenex aim to provide consultancy services and contribute to research and development projects with existing clients through knowledge gain relating to the application of V2G.

CHAPTER TWO

ELECTRIC VEHICLES AND THE WIDER ENERGY SYSTEM

2.1 INTRODUCTION

Uptake of electric vehicles (EVs) in the UK is increasing, with the Society of Motor Manufacturers and Traders (SMMT) reporting 47,690 ultra-low emission vehicles (ULEVs) registered in the UK between January 2011 and December 2015 [37]. Extrapolating the data from the SMMT reporting since January 2011, the Office for Low Emission Vehicles (OLEV) reported the contribution of ULEVs to total UK vehicle registrations was over 1% at the end of 2014, beginning of 2015 and is set to increase further [38]. This is shown in Figure 5, where a steep incline is evident from July 2014 onwards. This increase in ULEV numbers is due to a variety of contributing factors including Government legislation and plug-in car grants, along with improved air quality measures and reduced fuel costs. The UK Government plan that by 2040, all new vehicles purchased in the UK will be ULEV [38].

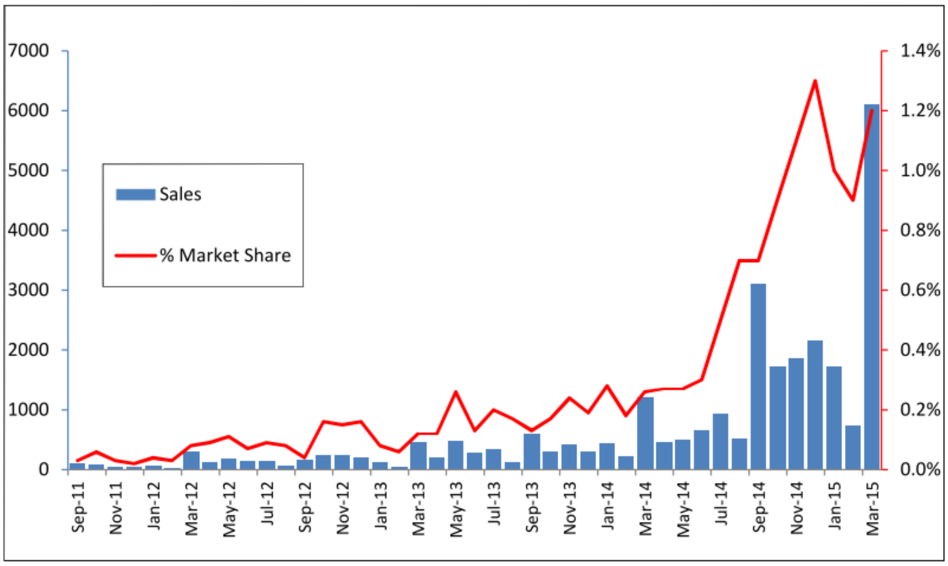


Figure 5 – OLEV reporting on SMMT ULEV registration numbers from 2011 to 2015 [38]

Decarbonisation of UK electricity generation is set to cause large variations in supply, with renewable generation more intermittent than traditional fossil fuel generated electricity, being largely dependent upon environmental factors such as sunlight and wind [39]. This presents an increasing need for energy storage solutions to provide a regulated, demand driven electricity supply at no detriment to the consumer. Replacing existing aging power plants with new generation and storage technology requires large financial investment in infrastructure, research and development and technology procurement [40].

One opportunity increasing ULEV numbers provides is the utilisation of existing storage assets by using EVs as energy stores. National Grid (NG) and Ricardo published a report in 2011 exploring the usefulness of EVs as energy assets to support existing grid response services, highlighting a significant shortfall by 2020 for a generation mix with increasing renewable input [41]. Through the exploration of building energy demands in the UK it can be concluded there may be economic and operational benefits in utilising EVs to distribute excess energy around the grid throughout the day. However, vehicle usage profiles will play an important role in assessing the viability of this scenario.

2.2 WHY ELECTRIC VEHICLES?

Whilst the SMMT report increasing EV uptake numbers, barriers to uptake include negative public perception to cost, driving experience and adaptability requirements. In 2008, OLEV and the Technology Strategy Board (now Innovate UK) jointly funded a research programme to support the development of EVs and generate an understanding of user perceptions in the UK [42]. Nearly 350 electric vehicles were involved, with over 51,000 charging events taking place over the duration of the trial [42]. The majority of participants found their perceptions about driving experience to be false, with little adaptation and performance compromise required [42]. Overall, participants found charging to be easier than expected and range anxiety was uncommon, with the average journey only 5.1 miles [42]. Conversely, Accenture undertook a European wide study into consumer preferences, with initial investment cost representing a significant barrier to uptake along with the limit to trip distance [43]. The trial covered over 7,000 EVs and findings contradicted those from the OLEV funded trial. Charging infrastructure was concluded to present issues to users, with further improvements in speed and ease of use required to instil confidence in the trial participants [43]. This difference of opinion between the two trials is likely as a result of different EV driving patterns, number of charging locations, ease of access and distance travelled by trial participants.

A compromise to pure EVs is hybrid vehicles, offering the range of a conventional internal combustion engine (ICE), with improved environmental credentials. Plug-in hybrids (PHEV) will bridge the gap for pure EVs until the range availability is large enough to ensure they are comparable to the ICE. Element Energy (EE) have predicted an uptake pathway of a 16% share of the vehicle market by 2020 for PHEVs and zero emission vehicles, increasing to 60% by 2030, with the expectation by 2050 the vehicle parc will be nearly entirely decarbonised [13].

2.2.1 ENVIRONMENTAL BENEFITS

The UK has some of the poorest air quality figures in Europe, with a large area of the country over the limit for acceptable airborne particulate levels (Figure 6) [44]. It is estimated as many as 29,000 deaths per annum are accelerated as a result of poor air quality in the UK [45].

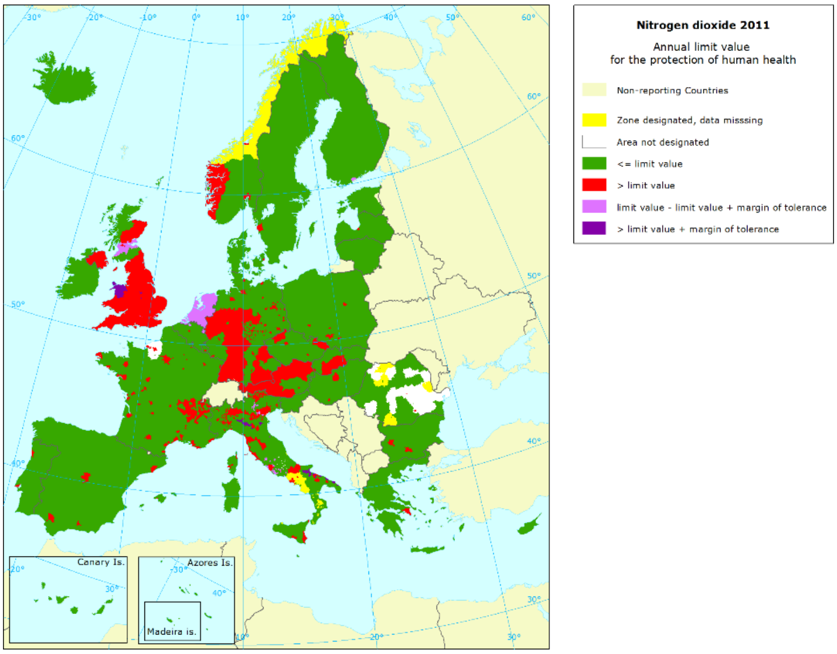


Figure 6 – Europe air quality map showing the majority of the UK as a red danger zone [44]

Air pollution can reduce life expectancy by up to six months due to the aggravation of existing respiratory conditions by airborne particulates [45]. Transport is the major contributor to air and noise pollution in the UK, with 60% of the Nitrogen Oxide (NOx) particulates in the atmosphere from transport [45]. UK NOx hotspots are shown in Figure 7, with poor air quality focusing on large population areas including London, Birmingham, Liverpool, Manchester and Newcastle [46]. Improvements in air quality have a direct correlation with reductions in vehicle use, introduction of low emission vehicles and improvements in fossil fuel driven vehicle technology [46].

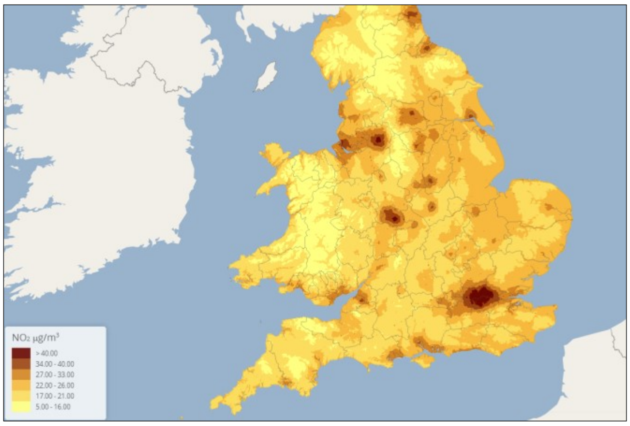


Figure 7 – UK Nitrogen Oxide emission levels by location [46]

Soret et al. [47] conducted an analysis of the potential improvements to air quality by replacing traditional ICE vehicles with pure EVs, PHEVs and hybrid EVs at a variety of uptake scenarios. The study explored the potential impact to the air and environmental quality of Barcelona and Madrid due to road transport being the largest emissions source in the cities [47]. They concluded the major air quality savings were in the reduction of NOx in the atmosphere, with a 40% adoption rate reducing emissions between 11 and 17% [47]. These seems to be fairly low figures in comparison to the required uptake rate and the authors identified a requirement to improve management strategies in order to see significant air quality improvements [47].

Road transport accounts for around 92% of total transport emissions in the UK, with the transport sector second largest by emissions, at 21% of total greenhouse gas (GHG) emissions in 2013 [48][3]. EVs represent around a 20-40% CO_2 saving compared to a petrol or diesel car under the UK's 2013 grid generation mix [49]. Increasing renewable generation into the grid over the coming years will increase this saving figure, with deployment of renewable energy generation across the UK expected to reduce emissions to 355MT CO_2 by 2020, a 40% saving [40]. However, considering the manufacturing process these savings may not be quite so impressive. Hawkins et al. [50] conducted a lifecycle analysis of EVs from production to decommissioning and found that whilst greenhouse gas (GHG) emissions were reduced, they have the potential to increase ecological and human toxicity and metal depletion impacts due to the supply chain. The authors also state the lifetime of the vehicle is important to establishing the overall global warming savings potential compared to ICE vehicles [50]. The greater the lifetime, the greater the comparative environmental savings impact, with the overall outputs from the study indicating improvements in the EV supply chain is of great importance if they are to become a true environmental improvement to traditional vehicle types [50].

2.2.2 CHARGING INFRASTRUCTURE

EV charging infrastructure is vital to the success of EV uptake in the UK due to the significantly shorter trip durations when compared to conventional vehicles due to a smaller driving range [51]. Charging infrastructure consists of three main types; slow chargers (up to 3kW), fast charging (7-22kW) and rapid charging (typically 40 to 90kW). A summary of the charge point types and their specifications is given in Table 1.

Table 1 – Example charging station ratings (taken from [52]*)*

Charge Point Power Rating	**Power Supply Requirement**	**Approx. Charge Time**
3kW AC	13/16A 220-240V	6-8Hr
7kW AC	32A 220-240V	3-4Hr
21kW AC	32A 415V	1-2Hr
50kW DC	80A 415V	20-30mins

The location of charging stations across the UK is widespread, with Figure 8 demonstrating the multiple locations [53]. Whilst already fairly extensive, increasing the number of charging stations across the UK is important to ensuring timely uptake of the technology [51].

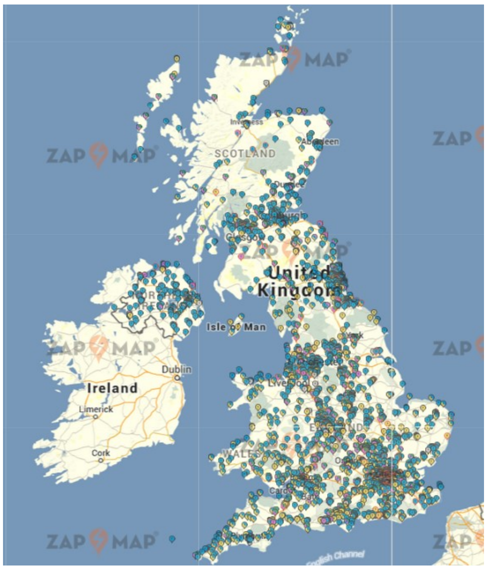


Figure 8 – Charge point locations in the UK [53]

The ULEV uptake pathway predicted by EE is heavily supported by OLEV, with the Plug-in Car Grant providing £400 million of funding to reduce the purchase price of ULEVs for customers. The scheme allows 35% of the price of a car to be paid for by the grant, up to a value of £5,000 and 20% off the price of a van, up to a maximum of £8,000 [54]. OLEV attribute the increasing success of ULEVs to this grant, along with the charging point schemes that have also been offered, including Plugged-in Places (PiP) and the electric vehicle homecharge scheme [55][56]. By March 2013, PiP had facilitated the installation of over 4,000 charging points, 65% with public access [55]. The homecharge scheme has run in two parts, with up to 75% of the installation cost for a charging post being funded through the scheme [57].

There has been much research into the development of models to predict the best location of charging stations based upon driver behaviour. Wang et al. [58] developed a non-linear multi-objective planning tool to predict the most suitable location of charging stations based on characteristics such as planning requirements, the power network capabilities, consumer practice and EV sustainable development. The final output was the creation of an algorithm able to predict the most suitable location of charging points in a changing energy and EV landscape [58]. Jia et al. [59] performed a similar analysis for a small area in Beijing, using population rates within the city and forecasting EV uptake in combination with calculating average daily mileage and energy consumption. Charging demand was divided into slow, medium and rapid, with the planning developed around each charge type providing different results due to infrastructure and ease of access [59]. Overall results indicated rapid charging was best placed at road sides, with slower charging more suitable for inner city car parks [59]. This largely correlates with the UK charging infrastructure, with rapid charging largely occurring at motorway service stations and on busy A roads. However, Amsterdam Schiphol Airport have implemented EV taxis, indicating the need for city centre based rapid charging may become more prevalent in the future as EV and PHEV uptake increases.

Current charging infrastructure in the UK is largely located to provide the vehicle user with easy access for re-charging, with charging occurring as soon as the vehicle is plugged in [42]. However, with increasing vehicle numbers, a lack of managed charging could present issues with overloading of the electricity network. EV charging and usage models exist that explore aggregated charging of multiple EVs. One such example is the model created by Druitt and Früh [60] that follows electricity market pricing. The research used a stochastic trip generation profile and simulated 1000 EVs with random sampling of journey distributions [60]. The model looked to explore how managed charging can contribute to demand management and network grid balancing [60]. The research concluded that users would benefit from flexible electricity buying/ selling tariff structures and user demand driven charging [60]. However, the research does make several assumptions as to vehicle destination and therefore overall availability for local network balancing. Additionally, network demand data was based upon NG profiles as opposed to high grain details of specific network requirements, potentially making the results less accurate than would be possible with low voltage network data [60].

Mal et al. [61] also identified smart charging (managed, intelligently controlled charging) as an effective method of avoiding network overloading during peak demand. They calculated a 7% cost saving with charge scheduling and a 56% decrease in peak load for drivers with a variable drive schedule compared to an unmanaged system [61]. Hadley and Tsvetkova [62] identified studies in which PHEVs were preferred to pure EVs, indicating the necessity in understanding the grid support opportunities for PHEVs and PEVs. Whilst PHEV charging represents a smaller charging demand on the network than the larger batteries of pure EVs, aggregated demand can still cause performance reductions and network overloading if uncontrolled [63]. Deilami et al. [63] modelled uncoordinated charging of PEVs vs. real-time smart load management charging to demonstrate the reduced network impact through controlled charging. The model looked at random arrival and departure patterns of available 10kWh PEV batteries to demonstrate effective worst case scenario managed charging success [63].

Using Digby, Nova Scotia in Canada as a case study, Pearra and Swan [64] demonstrated the benefits of smart charging through evaluation of three EV charging strategies; convenience, time of day (based on electricity tariffs) and smart charging. Through smart charging they made an additional

3MW of capacity available to export during peak demand times and increased the charging of EVs through renewable generation by 73% [64].

A summary of the perceived benefits of EVs in the UK is given in Table 2.

Table 2 – Summary of the perceived benefits of EVs to the UK

Perceived Benefit or Policy	**Value Type**	**Quantified Benefit**
ULEV Car/ Van Grant	Economic	Cars – 35% off cost of new vehicle up to £5,000 Vans – 20% off up to a value of £8,000 [54].
Plugged-in Places Grant	Economic and infrastructure	More than 4,000 charge points installed UK wide with around 65% with public access [55].
EV homecharge scheme	Economic	£15 million grant funding for domestic charging points [56].
Air quality	Environmental and health	NOx and particulates reduction – 11 to 17% reduction from 40% EV adoption rate [47]. CO_2 savings – 0.6 TCO_2 per vehicle per annum through PV smart charge/ discharge [65].
Grid security	Infrastructure and energy	Estimated as much as 11.3GWh of storage capacity available through V2G provision [40].

2.2.3 VEHICLE-TO-GRID TECHNOLOGY

The traditional UK electricity grid operates through meeting the electricity demands of many from a relatively small number of power stations [66]. The intermittancy of the future grid requires predictability within the control systems, along with more advanced control of the frequency, voltage and current across the network [66]. Whilst EVs will only add to the complexity requirements for control of the grid, they can also offer support through vehicle-to-grid (V2G) technology. V2G allows the vehicles to act as battery stores whilst stationary, providing energy back to buildings or the grid through a bi-directional inverter. Navigant suggest that assuming a daily average ~16.2kWh per vehicle is available for grid balancing services in the UK and this value is applied to the predicted UK EV number by 2020, this represents ~11.3GWh of energy storage capacity assuming all vehicle are connected at the same time [40]. The suggested benefits of utilising EVs as battery storage (BS) is the management of energy loads within local networks and the provision of EVs for peak shaving services for NG [67]. Management of fixed asset storage is fairly easy to regulate, however EVs pose additional variables found with standalone systems such as vehicle use, journey requirements and location.

Loisel et al. [65] looked at deployment of V2G technology in Germany and found no economic benefit to the user based upon the current pricing structure available, suggesting the necessity for creating user based charging tariffs. This was due to a miss-alignment of EV charging, discharging availability, high penetration of renewables into the grid and cheap electricity rates when the vehicles were available to discharge. Nonetheless, environmental savings by work place EV charging from PV generation were calculated to be as much as 0.6 tonnes of CO_2 per vehicle per annum [65]. Through this scenario, EVs can act alongside the PV as a distributed energy resource, acting as a dynamic energy load once connected to either an aggregator or energy supplier, allowing the provision of ad-hoc peak shaving services [65].

There are several models that attempt to accurately predict the suitability of EVs in providing grid support or peak shaving services through V2G. One approach employed by Bustos-Turu et al. [68] is using an Agent Based Model (ABM) to simulate EV usage and therefore battery availability. The premise of ABM is around the idea of autonomous entities or "Agents" [69]. Agents act to perform specific tasks or "goals" within their environment and each other if necessary [70]. Due to their autonomous nature, agents are also able to adapt and modify their behaviour in order to achieve their goals [71]. The methodology for modelling complex systems can be described based upon the viewpoint from which one is modelling. The model created by Bustos-Turu et al. [68] aggregates vehicle availability and focuses on the flexibility of loads as opposed to simulating high resolution vehicle usage data for a variety of vehicle types.

Much of the research identified by the author follows a similar pattern, with the focus on aggregated averaged information as opposed to simulated usage and battery modelling. White and Zhang [72] evaluated the use of EVs for frequency regulation by calculating the average number of miles travelled by groups of New York residents. This information was then fed into a profit calculation equation to evaluate the average annual profits from V2G participation [72]. Through this study, it is identified that the use of V2G causes battery degradation issues due to the increased cycling [72]. As such, they produce the following equation to calculate the cost of battery degradation in £/kWh of electricity throughput;

$$C_d = \frac{c_b + C_l}{L_c \cdot E \cdot DoD}$$

(1) [72]

Where; c_b is the cost of replacing the battery, C_l is the labour cost to replace the battery, L_c is the battery lifetime in number of cycles at a certain depth of discharge, E is the total battery capacity and DoD is the depth of discharge for L_c [72]. The results from their analysis agreed with Loisel et al. [65], with the economic analysis suggesting little economic benefit to the EV user in signing up to a V2G programme to provide peak shaving services. However, the use of EVs for grid regulation proved much more lucrative and the authors suggest a scheme based on daily regulation with peak reduction employed when electricity demand is high [65].

The impact of battery degradation has been explored at a chemical level by Waag et al. [73] and Ecker et al. [74] who investigate the impact a variety of variables have on battery degradation including; cycling, thermal aging, resistance and state of charge (SoC). The research conducted by Waag et al. showed that depending on the SoC of the battery, the relative resistance varied quite dramatically [73]. Temperature was also shown to have an impact on cell degradation, with temperature extremes having the greatest impact [73]. Results show that cycling around the middle section of the battery SoC, i.e. +/- 10% of 50% SoC, prolonged battery life when compared with operation at much larger variations [73]. The research conducted by Ecker et al. [74] focuses on cell aging in multiple ways such as temperature changes, cycling around different SoC and cycle size. Results showed that the number of equivalent full battery cycles achieved by the lithium-ion battery type tests increased dramatically if the batteries were only cycled around the middle portion of the SoC, irrelevant of the influencing variable being tested [74]. Cycling above +/- 10% from the 50% point started to dramatically reduce the battery life which directly supports the results obtained by Waag et al. [73][74]. These results differ from statements made by leading vehicle manufacturers, who claim V2G cycling does not increase battery degradation. This indicates a lack of transparency between manufacturers and academic institutions, something that could be beneficial to the acceleration of this industry.

Whilst EV uptake is anticipated to increase rapidly by 2030, alternative vehicle types such as PHEVs offer a viable alternative to the shorter range of EVs [75]. PHEVs generally have a smaller battery than pure EVs, but are still able to offer peak shaving services with effective intelligent charging [76]. Through facilitated smart charging, (in which charging of the EV is bounded by requirements limits set by the user) management of PHEVs could also provide effective peak shaving opportunities [76]. Aryanezhad et al. [77] developed a Monte Carlo based algorithm to manage the reliability of smart grids with PHEVs and renewable generation installed. The authors attribute the unmanaged charging of PHEVs to have potentially significant negative impacts to the reliability of the electricity grid [77]. This resulted in the creation of an algorithm to manage the charging and V2G applications within the smart grid environment to prevent negative impacts such as overloading [77]. The results output from the study indicated that with the management algorithm implemented, there was a marked improvement to the reliability of the grid when compared to non-managed charging. The V2G enabled systems also acted as energy storage for the excess renewable generation, further flattening the peaks in demand on the system [77].

Lund and Kempton [78] also looked at combining renewables with V2G applications, using two real-world example national energy systems - Denmark and a higher carbon intensity comparison - to assess the potential for V2G to improve efficiency and reduce the carbon intensity of the electricity grid. Using the software EnergyPlan, the study looks at a voltage transmission network and the impact EVs with V2G could have on supporting the addition of wind generation [78]. Results showed that the higher the integration of V2G into the energy system, the greater the usable electricity output without the need to increase electricity production [78]. This is in contrast to the results obtained by Fattori et al. [79] who explored the integration of photovoltaics (PV) with EVs in a smart grid environment. They created an EV Learning Model which used a linear programming approach to simulate the relationships between EV charging and V2G applications [79]. The aim of the model was to satisfy the electricity demand of the smart grid at the lowest operating cost, looking specially at using EVs in combination with PV [79]. The model is relatively complex in its operation, able to simulate the energy flows that occur within an energy system and allows the user to choose the working conditions they wish to analyse, such as mid-week or weekends and seasonal variation [79]. Results from analysis within the model indicated that the PV generation and EV charging patterns of the case study analysed did not match, meaning combining EVs with PV was of no economic benefit [79]. This indicates that battery storage is key to achieving full utilisation of EV charging from PV.

Saber and Venayagamoorthy [80] used Particle Swarm Optimisation (PSO) to evaluate the unit commitment of V2G within a network. Unit commitment refers to an optimisation problem of generation units where constraints, environments and loads vary over time [81]. By using PSO as an optimisation tool, the authors were able to simulate the anticipated profits received from operating V2G [80]. An alternative modelling technique employed by Shepehry et al. [82] was to create a stochastic model to evaluate the optimal location of charging points in car parks with respect to the distribution network. Haghi and Qu [83] also used a stochastic based approach to assess the potential for V2G to provide voltage support, reducing the need for network upgrades. The Markov Chain based method provided an optimisation and control framework for the future management of V2G related storage [83]. Other authors interested in how V2G can provide support to power networks were Jian et al. [84]. They proposed an event-triggered scheduling model that relates to a stochastic EV connection with a smart grid [84]. They recommended several key points within their dynamic programming problem, stating that EVs still need enough energy to make a return journey after providing V2G services and the charge and discharge of the vehicle should never exceed the available capacity of the battery [84]. Overall results from their research indicated that EVs with V2G could decrease the total load power curves of the network and therefore improve efficiency and the robustness of the network [84]. The results from Jian et al. [84] concur with the analysis conducted by Sarabi and Kefsi [85], who explored the potential of reducing peak power demand through managed EV charging. Through a dynamic programming solution, in which the model searches for the optimal solution to the demand and charging schedule, peak demand was shown to reduce by 17% when looking at the winter load profile of France [85].

2.2.4 AGGREGATION SERVICES

Disparate asset utilisation through aggregation services is a well-established industry in the UK energy sector, with Commercial Aggregation Service Providers aggregating smaller generation sites to address balancing service requirements [86]. Companies such as Open Energi, EDF Energy and Flexitricity all provide aggregation services to smaller generators and suppliers [86]. Traditional aggregation of assets occurs with generators and uninterruptible power supplies (UPS) being used to reduce the peaks in electrical demand profiles [87].

Literature suggests that through the exploitation of smart meters and the advanced control of battery storage assets (including EVs) peak energy demand could be minimised when managed by a Virtual Power Plant (VPP). A VPP exploits geographically dispersed generation and storage assets through online software suites, designed to provide connection and control to all Distributed Energy Resources (DER) available to the VPP operator [88]. They provide aggregation models for the management and delivery of DERs, such as EVs [89]. VPPs can be categorised depending upon their overarching goal, whether that be to increase efficiency, improve profits or reduce consumption [90]. There are two key characterisation models; the commercial virtual power plant (CVPP) and technical virtual power plant (TVPP) [91]. CVPPs look to exploit the outputs from the VPP profitably through a metering contract to gain better value for aggregated energy generation [92]. The TVPP uses outputs from the CVPP to make informed decisions on network constraints and network characterisation [93]. The control system obtains information from all available assets to determine the aggregated support availability, creating a virtual 'micro-grid' type network accessible to various energy markets, similar to conventional power plants [94][90]. VPPs allow the aggregator to group customers based upon location, generation type, or general typology to better enable them to provide services to the grid [90]. This allows greater flexibility for energy trading within energy markets with generators that would otherwise be too dispersed to have any impact [90].

Several reviews have been conducted into the suitability of using a VPP for the management of distributed EVs. A variety of VPP structures are proposed, with Raab et al. [89] suggesting a direct, hierarchical or distributed approach to DER management whilst Monyei et al. [93] use the previously mentioned CVPP and TVPP terminology. This lack of correlation between descriptions and structure suggests a lack of evolution in the development of VPP technology. However, what is clear is the goal driven nature of all the VPPs in providing cost and emissions savings through deployment of the aggregation technology. Arslan and Karasan [95] evaluated the cost and emissions impact of employing a VPP for EV management and resource scheduling. Their case study looked at California and evaluated real world data to calculate a cost saving of 29.5% and NOx reduction of 83% due to EV uptake through the VPP scheme [95]. Dietrich et al. [96] also found significant savings could be achieved through implementation of a VPP for DER including storage and renewable generation. They concluded the organisation and type of VPP was crucial in providing economic benefit, suggesting a self-supplying VPP in which all generation assets are used within the local network was more beneficial than one with external export [96].

It is evident development of a clear VPP structure with pre-defined goals is crucial to the outcome and economic benefit of VPPs. Economic benefit is of course, also dependent upon the payment price of the electricity generated within the VPP assets. Evaluation of the most appropriate tariff for the VPP is also a key variable to their success and payment for asset utilisation is crucial to the adoption of V2G for EV users. Early take up schemes could follow a similar pattern to that of micro generation scale photovoltaic (PV) technology with the Feed-in-Tariff (FIT). PV owners signed up to the scheme receive money for the generation of all electricity from the system in addition to an export payment for any excess generation fed into the UK grid [97]. The original tariff payments were £0.413/kWh for retrofit systems less than 4kW in size and £0.361/kWh for new build installations [98]. This caused the installation of over 600,000 PV arrays, amounting to 3,075MW of generation under the FIT (calculated from [19] by DECC).

Whilst this model is transposable to storage technology such as BS and EVs, payment parameters and tariff structures are sensitive to input requirements [99]. If looking at using EV storage for direct building support, the nature of the billing scheme employed by the building is significant. Commercial buildings operate under several standard payment types including Time of Use Tariff (TOUT) and Triads. TOUT include schemes such as Economy 7, in which consumers pay different prices for the time of the day, with night time having 7 hours of cheaper electricity than in the day [100]. TOUT presents the opportunity for EVs to supply energy directly to the building during peak demand times when tariffs are highest. Development of TOUT is likely to increase the number of EV users that will sign up to a V2G scheme, allowing them to receive financial incentive due to high day time payments for excess electricity and reduced charging costs during the night.

Triads charges are billed for the three half hours in the UK with the highest demand for the whole year [101]. This is based on NG data for the highest maximum demand periods, with reconciliation occurring on the following years bill [102]. This system enables large half-hourly metered consumers to buy their electricity at a lower fixed price directly from the wholesale market for the baseline electricity consumption of the site. The extremely high electricity cost incurred during the triad periods are then added on top to encourage large demand sites to reduce during these peak times [103]. Through using EVs to supply energy to a building, under current legislation, the energy consumed during these triad periods could be reduced, therefore reducing the energy bill of the commercial consumer. The increasing uptake of EVs in combination with their sizeable battery capacities makes them an interesting vehicle for exploration of additional uses to traditional transport options and their potential to operate as temporary energy stores makes them a diverse and interesting area of study.

2.3 SUPPLY AND DEMAND MANAGEMENT

The employment of BS in EVs is potentially useful for the three key markets in the UK; local re-distribution of energy, ancillary services and wholesale market trading. Ancillary services are defined by Swissgrid as *"…services provided by grid operators to customers in addition to the transmission and distribution of electrical energy."* [104]. Balancing services provide additional support through running additional power plants or aggregating energy sources to provide an energy buffer when demand is greatest [105]. Three types of balancing services are currently utilised by the NG; frequency response, fast response and short term operating reserves [105]. The use of balancing services introduces a significant cost to the NG, with £803 million spent on reserve and frequency response services in 2012/ 2013 [106][41]. As such, alternative methods for meeting this electricity demand are desirable (Figure 9) [41]. System Operators (SO) (NG in the UK) perform system balancing in order to balance the demand and supply of electricity across the transmission network to maintain security and quality of supply [107]. Due to the unavailability of large quantities of electricity storage in the UK, energy balancing is required to ensure supply meets demand, along with preventing damage to the transmission system [105]. Balancing is met through several forms, as mentioned previously; short term responses, management of network frequency and management of capacity [105]. Ancillary services include reactive power and frequency response services [108].

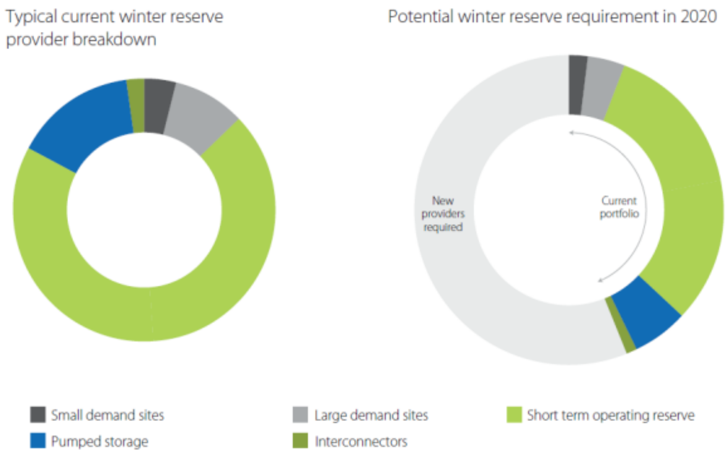


Figure 9 – Current and future electricity reserves [41]

2.3.1 The UK Wholesale Energy Market

The wholesale market is the platform in which suppliers and generators meet to trade electricity sold to domestic and business consumers and is regulated by the Office for Gas and Electricity Markets (Ofgem) [109]. It allows customers to choose between suppliers for the best deal and suppliers to purchase electricity from their chosen generators [108]. This also means companies without any physical means of generating or demanding electricity are able to trade as 'non-physical traders', ensuring a fair price is paid for electricity from the supplier of choice [108]. Trading occurs in half hour blocks called settlement periods, meaning suppliers must estimate their customers electrical demand to the nearest hour [108][109]. Long term contracts enable suppliers to provide fixed price deals to customers, however this provides less certainty in accurately predicting the amount of energy required [109]. When total wholesale supply is less than forecasted the NG will employ balancing actions [109]. Suppliers are expected to predict demand up to an hour before the settlement periods and generators and suppliers are expected to produce their stated requirement or generation [108]. However in reality this may not happen, with generators unable to meet demand, errors in the transmission of the electricity or suppliers incorrectly predicting demand [108]. If generators produce too much energy they are able to trade with the system operator and offer the excess generation at a set price, making the system flexible enough to ensure an active trading scheme and suppliers and traders are able to remain competitive [108][110]. High cost 'fines' exist for generators or suppliers that do not accurately predict supply and demand, with generators required to pay for the excess if not enough was generated and suppliers required to buy additional energy if too much was consumed during the period [108]. Several key auctions or markets have been identified as potentially suitable for EV buy-in with the wholesale market, these are; the day-ahead auction, half-hour day-ahead auction and the spot market.

The day-ahead auction is based on the simple concept of trading for generation into the auction a day-ahead of the selected time slot [111]. The auction operated by APX Power UK is a double-sided blind auction, meaning neither buyers or sellers can see competitor bids and multiple bids per half-hour slot can be made by buyers and sellers [111]. In a 24-hour period the power delivery volume into this auction doesn't change dramatically, as can be seen with the example given in Figure 10, which shows the volume delivered and average price paid per MWh [111].

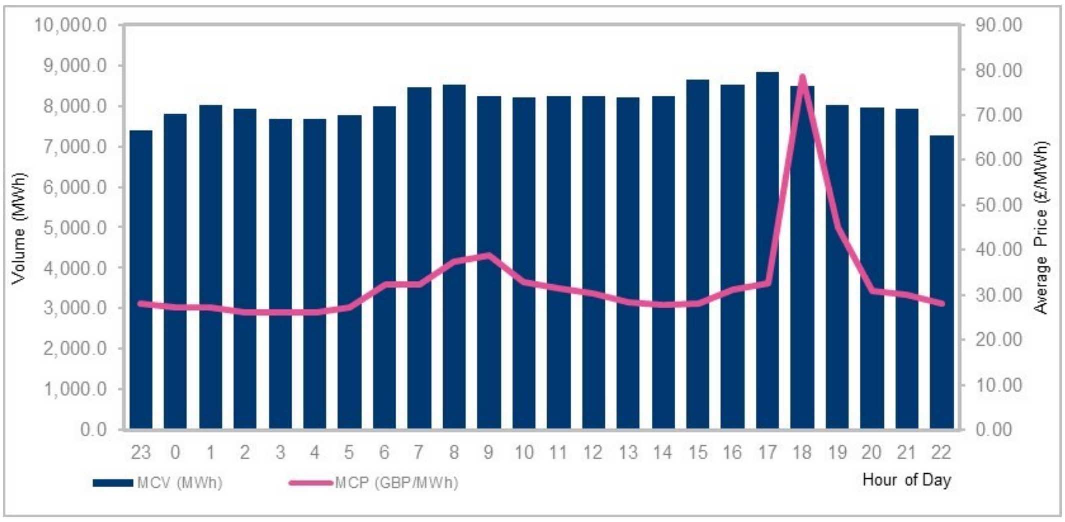


Figure 10 – APX results summary for day-ahead auction (15/03/2016) (data source: [111]*)*

The spot market is a little more complex than day-ahead auctioning as it is used predominantly for balancing and trading purposes [112]. Various 'products' or contracts can be bought into by generators and a summary of those offered by APX Power UK are given in Table 3. The payment opportunities for the spot market are more limited due to the trading functionality, with price varying little from month to month [112].

Table 3 – APX Power UK Spot Market trading options (based on information taken from [112]*)*

Contract Type	**Period of Coverage**	**Duration (Hours)**	**Trade Opening**
4-hour block	6 blocks per day, starting at 23:00 and ending at 23:00.	4	Rolling 7 days
2-hour block	12 blocks per day, starting at 23:00 and ending at 23:00.	2	49 ½ hours prior to delivery
1-hour block	24 blocks per day, starting at 23:00 and ending at 23:00.	1	48 hours prior to delivery
½ hour block	48 blocks per day, starting at 00:00 and ending at 00:00.	½	49 ½ hours prior to delivery

2.3.2 Frequency Response Services

The frequency of the power signal transmitted in the electricity network is constantly changing and is controlled in pseudo-real time through second-by-second balancing of the system demand and total generation [113]. The service is split into several categories; mandatory frequency response, firm frequency response (FFR) and frequency control by demand management [113]. Frequency of the grid changes depending on if generation is greater than demand (frequency increases) or demand is greater than generation (frequency decreases) [113]. Mandatory frequency response is provided by generators within their General Licence, with all generators required to be able to provide the service if called upon [114]. The service keeps the frequency of the network between statutory and operational limits through either; primary, secondary or high frequency response [114]. Due to the response requirement for those signed into the service, it is potentially unsuitable for EVs with V2G to support this service unless other sources of more rapid response are combined with EVs. Frequency Control by Demand Management operates through providing frequency management by interrupting demand customers for a 30 minute duration for a payment fee [115]. Finally, Firm Frequency Response is open to existing balancing providers, generators and new providers through a tender process [116]. The typical delivery requirements are given in Table 4.

Table 4 – Firm Frequency Response delivery requirements (taken from [116]*)*

Requirement	**FFR**
Minimum Generation Amount	10MW.
Response Time	High Freq: 10s and sustained indefinitely. Low Freq Primary: 10s and sustained for 20s. Low Freq Secondary: 30s and sustained for 30 mins.
Run Time	No limitation other than plant requirement.
Ability to Combine Loads	Yes, so long as it is equal or more than 10MW total aggregated and run through a single point of despatch.

Due to the rapid response time required for FFR, as seen in Table 2 it is unlikely to be a suitable market for sole aggregated EV support. In combination with other supply sources they may prove useful, however due to the switching time observed within existing V2G systems, FFR is unsuitable.

2.3.2 RESERVE SERVICES

When generation and demand does not match with the network requirement, the SO requires generators and demand to either increase or reduce based on the UK demand [117]. There are four services that come under Reserve Services; Fast Reserve, Short Term Operating Reserve (STOR), BM Start-up and Demand Management [117]. Fast Reserve is the quickest of the reactive services, with a 2 minute response time and with a minimum of 50MW delivered per call out and 15 minutes minimum of sustained delivery [118]. This service is nominally used to provide very quick delivery of active power through an increased generation output or decreased consumption, however it can also be used for frequency balancing in some cases [118]. BM Start-up is a process by which NG will send a request for a generator to begin start-up, with the proviso the system is able to synchronise within the 89 minute Balancing Mechanism time scale [118]. This service also presents a requirement to have the ability to turn off the generator if required or maintain it in standby mode until required [118]. Both Fast Reserve and BM Start-Up are unsuitable for EVs as modes of support due to the nature of the energy storage and the synchronisation requirements demanded from the market. However, STOR requirements are more achievable, with the minimum generation requirement at 3MW (see Table 5) [119]. It is a pre-contracted balancing service, meaning the provider delivers to a contracted level of power when instructed to do so by the SO [119].

Table 5 – Short Term Operating Reserve (STOR) delivery requirements (taken from [119]*)*

Requirement	STOR
Minimum Generation Amount	3MW.
Response Time	Typically, 20 mins or less but can be up to 240mins.
Run time	At least 2 hours.
Frequency of delivery	At least 3 times per week.
Recovery period	No more than 1200 minutes.

Demand management would also be a possible market buy-in for systems with a large number of EVs on site. This requires the reduction of demand of customers for a 30 minute period where national demand is high and therefore statistically interruptions are likely to occur [115]. This enables the management of large frequency variations across the grid caused by significant events, such as the loss of a generator [115]. The participation requirements in Table 6 show the extremely small response time given for the demand load to respond. Depending upon the technical capabilities of the units connected to the vehicles, aggregated EVs could operate within this market.

Table 6 – Frequency control by demand management delivery requirements [115]

Requirement	Frequency control by Demand Management
Minimum Generation Amount	3MW.
Response Time	Within 2 second of instruction.
Run Time	At least 30 minutes.
Frequency of Delivery	10-30 times per year on average.

2.3.3 THE CAPACITY MARKET

Through the Electricity Market Reform Act (EMR) the UK Government released a series of reforms to take place on the current UK electricity market to try and address some of the challenges of an aging electricity network [120]. These challenges include closure of power plants and therefore a reduction in capacity, increasing diversity of the generation mix and an increasing electricity demand [120]. Two key mechanisms were therefore proposed; Contracts for Difference (CfD) and the Capacity Market (CM) [120]. CfD is a price stabilisation tool to promote new investment in capital generation equipment, whilst the CM acts as a retainer service for reliable capacity to be called upon when required [120]. The CM enables NG to buy energy capacity in advance, ahead of delivery to guarantee investment in developing generation [121]. Trading occurs four years ahead of the required delivery date, with capacity requirements issued as a capacity demand curve [122]. Generators then buy into the scheme, bidding for energy contracts to provide the service demanded by the capacity curve [122]. A limit of 2MW de-Minimis has been set, under which any generation must be taken into an aggregation service [122]. The bidding and delivery requirements are set by NG for each individual participant in the CM depending upon their availability and NG requirements [122]. In combination with the capacity market, generators can buy into additional markets to generate extra income, such as the wholesale energy market. A summary of the known capacity market requirements is given in Table 7.

Table 7 – Capacity market delivery requirements (taken from [121]*)*

Requirement	**Capacity Market**
Minimum Generation Amount	2-50MW total generation obligation. A percentage of total obligation is specified when delivery warning is issued.
Warning Time	Around 4 hours before required delivery time.
Run time	As specified at time of demand.

2.3.4 ENERGY ARBITRAGE

Energy storage is the primary focus of energy arbitrage, where advantage is taken of differing electricity prices throughout the day to buy and sell energy for storage and provision [123]. Energy storage in the UK and worldwide is predominantly pumped hydro, covering around 99% of the worlds energy storage [124][125]. However, pumped hydro is expensive and inefficient and alternative sources of storage would be beneficial to increase storage provision for UK energy markets [124][126]. BS is classified by ELEXON as storage with a long discharge duration potential and low power rating, making it perfect for balancing services and the capacity market [127]. The US Department of Energy (DoE) suggest that analysis of the current US energy network provides little economic opportunity for energy arbitrage as a stand-alone economic model [128]. This assessment is based on the investment required for new storage infrastructure due to the very high production costs of storage technology [128]. Through the capacity market in the UK however, the UK Government has provided a platform for new technology to be built and developed for provision of future electricity generation [129].

2.3.5 VEHICLE-TO-GRID MARKET POTENTIAL

Research already conducted into the economic potential of EVs with V2G in relation to energy markets and local network demand reduction explores a variety of topics including demand side management (DSM), local and national level analysis and using a variety of modelling techniques. With regards to DSM, Mišák et al. [130] used an heuristic approach to explore the opportunities of DSM in off-grid scenarios. The research focused on a smart home environment rather than exploring EVs, but through intelligent scheduling they established that demand could be spread over a 24-hour period, removing demand peaks [130]. This increased renewable generation efficiency and reliability and therefore shortened the investment costs of the technology [130]. Bishop et al. [131] conducted research to assess the income required to be received by EV owners from an aggregator to make signing up to a V2G scheme worthwhile. Two groups of potential customers were considered; existing EV owners who would like to sign up to a V2G scheme and maintain or improve their financial situation; and new EV owners who would compare the economic costs with traditional ICE vehicles [131]. The research identified several potential markets of interest for V2G including using EVs as storage for off-peak electricity generation and supply to the network during peak times, reducing energy costs in homes and short duration, high power markets, for example STOR [131]. However, they state that FFR would be the most appropriate market in the UK for V2G aggregation buy-in. Based on the information collected through this thesis, this is identified as unachievable without aggregation alongside additional storage devices due to the slow start up times of the V2G infrastructure [131]. Of interest is the identification of capacity payments being the only profit making venture for V2G due to the high install costs and a study conducted based on the German energy market by Dallinger et al. [132] suggested a change to current market demands such as a V2G specific market is necessary in order for V2G be feasible in the long term [131].

Considering the market potential for BS, Hein et al. [133] reviewed the V2G market in comparison to used and new EV batteries for energy storage. They used system dynamics (SD) to model the competition amongst different approaches for using EVs as BS to support the grid [133]. Looking at a period of 2011 to 2020, they estimate annual profits to EV users at €360 when signing up to a V2G scheme in 2020 [133]. However, based on the vehicle modelling conducted, the authors predict large scale uptake of EVs with V2G is unlikely due to the high uncertainty surrounding the battery economics and technical elements of the system [133].

2.4 CHAPTER SUMMARY

Initial research undertaken as discussed here demonstrates that whilst the uptake of EVs is expected to increase dramatically over the coming years, barriers to full market penetration include public perception and cost. Due to the type of journeys EVs are likely to make, analysis already undertaken suggests grid support is possible. However, there are several barriers including the capability of the electricity grid, cost models available to incentivise consumers, the management system capable of controlling multiple, interchangeable assets and effects of V2G cycling on battery life. Relatively little is known about these variables as of yet and further research would provide more extensive information as to the issues faced with V2G in the UK.

Research specifically relating to the potential markets for EVs with V2G is limited, with the majority of research focusing on specific aspects of the network, smart grid or technology. The approaches taken in terms of the modelling and simulation in the research covered is instrumental in providing an evaluation of the potential modelling approach for the V2GFAE in the following chapters of this thesis. An evaluation of the modelling approaches utilised in the research reviewed is given in Table 8.

Several research gaps were identified within the literature reviewed and are detailed as follows:

1. Using EVs to provide peak shaving services at a local level to buildings such as commercial or domestic properties has been researched in some detail with respect to average, aggregated data. Little research into high resolution modelling of vehicle usage has been undertaken as of yet.
2. Utilisation of EVs for storage of excess PV generation to re-distribute into buildings during periods of high demand high cost, for example those buildings on TOUT or to reduce triad periods. Again, this research is sparse and little is known as to the impact TOUT will have on V2G scheme sign up.
3. Aggregation of EVs for supply into UK energy markets is under explored. Based on the information gathered through this literature review, the key markets to focus on have been identified as STOR and the capacity market. For this research, the wholesale energy market will also be explored in conjunction with the capacity market.
4. A lack of research in the area of vehicle usage and battery availability indicates an importance for a high resolution model that simulates vehicle patterns in order to establish possible support opportunities.

This literature review has provided a detailed overview of the current research and knowledge space with regards to electric vehicles and V2G. Specific attention was applied to previous economic research, with numerous knowledge gaps identified with regards to UK energy markets and the economic savings potential of V2G.

Table 8 – Review of modelling approaches and techniques used for V2G within the literature

Approach or Technique	Description	Advantages	Disadvantages
Agent Based Modelling	Systems are modelled using a bottom up approach as a set of agents acting with individual behaviours towards a desired objective [134].	Allows the dynamic behaviours of environments to be modelled [134].	Can be complex to model and should only really be used for systems with emergent behaviours.
Stochastic	Examples are Monte Carlo. They are common with financial modelling and look to estimate probabilities of events occurring using random variable generation [135].	Chance based modelling and can therefore base results on real-world data.	Generation of random numbers is often not entirely random and can therefore adversely affect outcomes.
Monte Carlo	Stochastic modelling method. Pseudo random numbers are generated from a probability distribution function [136].	See above.	See above.
System dynamics	Represent the system of interest as stocks and flows [134]. This is a continuous modelling and simulation approach [134]. Very similar to discrete event [137].	Wide applications including economics, politics and psychology. Allows for dynamic systems to be simulated effectively [137].	Usually higher-order using stochastic differential equations and therefore complexity can be lost [138].
Discrete event	Used for modelling queuing systems primarily due to the 'next event' methodology for management of the model behaviour [135].	Allows for tracking of the system behaviour due to the queuing structure. Can also view individual elements of the system as entities, or aggregate them together depending upon the decision outcome of the model [135].	Next step modelling, meaning one entity is modelled after the previous. There is therefore not as much flexibility in the system [135].
Particle Swarm Optimisation	Stochastic based optimisation technique that uses natural swarming behaviour, such as flocks of birds, as a basis for theory [139].	Simple mathematical basis and wide applications across multiple fields [139].	Random nature of swarming can be difficult to achieve [139].
Linear and non-linear programming	Method by which the system is either maximised or minimised depending upon the required output [140].	The simulations are deterministic or probabilistic [140]. Can use multiple variables to influence outcomes of simulation [140].	Model works within tightly defined boundaries which can obscure results due to potential non-real world based approach [140].

CHAPTER THREE

SYSTEM ARCHITECTURE SPECIFICATION

3.1 APPROACH

This section presents the approach taken in designing the system architecture and requirements capture for the Vehicle-to-Grid Feasibility Analysis Environment (V2GFAE) software. The technique for development of the software tool is through Model Driven Architecture (MDA) which supports the development of whole lifecycle engineering. Lifecycle engineering ensures the stakeholders' needs or requirements are met through efficient and organised stages as per the system lifecycle process [141]. Figure 11 demonstrates an example lifecycle process, adapted from the System Engineering Management Plan developed by the Ocean Observatories Initiative [142]. This describes the five key stages of the lifecycle process; design, develop, construct, deploy and disposal [142].

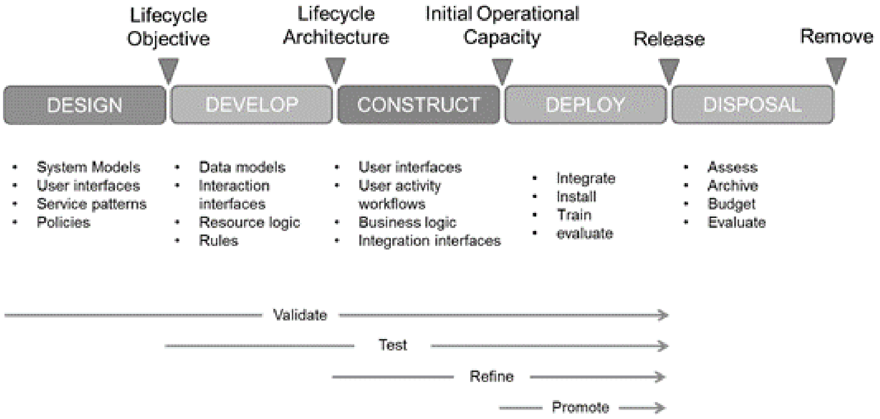


Figure 11 – System engineering lifecycle process diagram (adapted from [142]*)*

The International Council on Systems Engineering (INCOSE) [141] indicates system engineering tasks are usually focused around the beginning of a project lifecycle to ensure modification or alterations to the system are less likely due to effective planning and management at the beginning of the lifecycle. Imperative to this is the system requirements capture stage, with INCOSE [141] stating its purpose as being the following;

"…to transform the stakeholder, user-oriented view of desired capabilities into a technical view of a solution that meets the operational needs of the user."

Requirements capture is achieved by development of the system architecture including use cases, activity diagrams and class diagrams to build a detailed system description from which to develop the software. ISO/IEC/IEEE 29148:2011 [143] state the requirements engineering process must be iterative in order to develop an effective system and this is exemplified in Figure 12. Throughout the system lifecycle it is expected that requirements will develop and change over time, potentially changing the outcome of the overall system as they are referred back to the key stakeholders [141]. Trade-offs inevitably occur at some point throughout the lifecycle process and it is therefore important to record every iteration of the system requirements and perform regular checks with stakeholders.

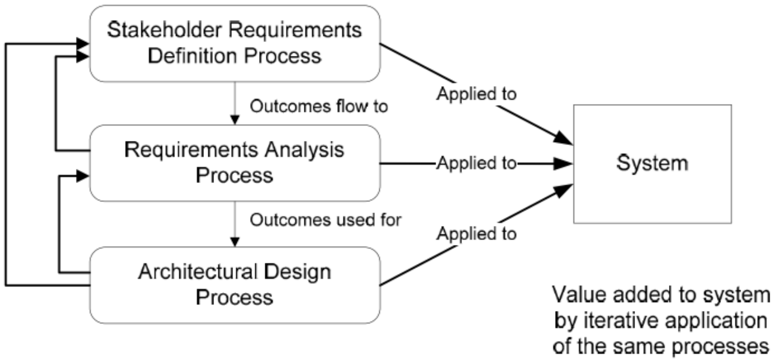


Figure 12 – Iterative system engineering development process [143]

In following the system lifecycle process and MDA approach to system architecture development, the requirements definition for the V2GFAE is built up to form a comprehensive specification for the software.

3.2 MODEL DRIVEN ARCHITECTURE

MDA was set up by the Object Management Group (OMG) to support the development of the full life cycle approach for physical, organisational and I.T. systems through models and system architecture [144]. Within this research, MDA is used as a tool for development of the specification and architecture of the V2GFAE software. This approach supports the entire systems engineering (SE) lifecycle approach, following the traditional methodology as shown in Figure 13. This chapter details the first three items of the SE 'vee', up to and including the high-level system design phase.

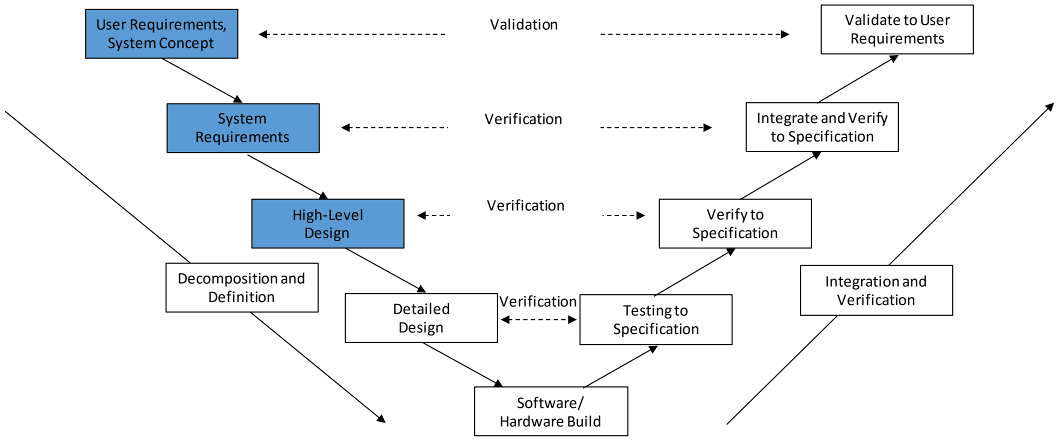


Figure 13 – Requirements and high level design phase of systems engineering 'vee' process

Systems engineering in the context described here is the process of creating, implementing, testing and validating a system for its chosen purpose. A system is defined by INCOSE [141] as *"…a combination of interacting elements organised to achieve one or more stated purposes".*

Development of a system architecture (SA) for the V2GFAE software through an MDA approach involves creation of a series of distinct models to represent key elements of the software with specific functionality [144]. A key tool used for system architecture creation and requirement capture is Unified Modelling Language (UML) and is considered to be the standard for object-oriented problem solving [145]. UML enables the system engineer to develop the information required within the system into a series of models that depict the overall system and information within it. It is through this approach that the V2GFAE will be built, with the initial requirements definition process forming the basis for the architectural framework.

3.3 SYSTEM ARCHITECTURE SPECIFICATION

The aim of this research is; *to create a platform from which to evaluate the investment opportunity of V2G in a local services case study for future energy scenarios.* This leads to the suggestion of a software platform or solution capable of analysing large amounts of information related to V2G energy support scenarios. This is the V2GFAE and is a software based analysis tool used in the evaluation of electric vehicles (EVs) as battery storage mediums. The end users will be employees of Cenex, who have provided a brief specification document as to the requirements of the project, previously scoped out in Chapter 1, Section 1.2 – Research Aims and Objectives (see Table 9).

Table 9 – Stakeholder project specification document

Stakeholder Project Specification Document

The primary driver for this research is derived from the industrial sponsor Cenex, who would like to provide consultancy services for customers wishing to understand the suitability of their fleet and /or building in utilising EVs for vehicle-to-grid (V2G) services. The overall aim of this research project is therefore to enable the evaluation of the investment opportunities for V2G (managed by a Virtual Power Plant (VPP)) in a local services scenario for future energy scenarios, facilitated through the creation of a software environment. The investment opportunity will be assessed in terms of two key areas; a) the anticipated local economic savings, such as clusters of buildings through peak shaving, time of use tariff support and PV charging integration; and b) the suitability of EVs with V2G to provide electricity to STOR and the Capacity Market. The software should be built/ coded in Matlab or Simulink to enable easy interfacing with other Matlab models within Cenex's portfolio.

The above aim can be broken down into several smaller objectives as follows;

1. Define the requirements for the research project through development of a systems architecture.
2. Identify the use cases for evaluation from the case study.
3. Specify and develop the scenarios used for evaluation of the case study within the software environment.
4. Using the requirements specified through development of the system architecture and the scenarios, create the software analysis environment.
5. Identify and validate the data from the provided case study for evaluation, using building aggregated demand, vehicle telemetry and PV generation data.
6. Using Manchester Science Park as a case study, test the software through the built-in local services scenarios.

These objectives will be used primarily to aid in answering several smaller questions using Manchester Science Park as a case study. These are:

1. What impact does the payment tariff for EV support have on the economic suitability of EVs to provide battery storage provision?
2. What impact does the vehicle usage profile have on the ability to provide battery storage, both locally and for energy market trading? Two usage profiles are of primary interest; commuting and pool vehicles.
3. What is the overall suitability of electric vehicles as battery storage devices? Is one energy scenario support option more suitable than another depending upon electricity provision requirements?

3.3.1 SOFTWARE PURPOSE AND CONTEXT

The software will enable a variety of data values to be input, along with key variables to be set/ selected allowing it to generate different energy scenarios for analysis. The software is able to explore two key areas of support for EVs; a) local energy systems, for example building clusters and b) market demand. By separately defining these two areas the software is therefore able to identify the suitability of EVs in providing electrical support to buildings within a local network, for example a street of houses or industrial park. In addition, the suitability of the same vehicles aggregated by a Virtual Power Plant (VPP) to provide electricity to energy markets can be assessed as a separate, comparative entity. This provides a platform to establish the most suitable support option for the

EVs within the energy environment being explored. This information is shown in a context diagram in Figure 14.

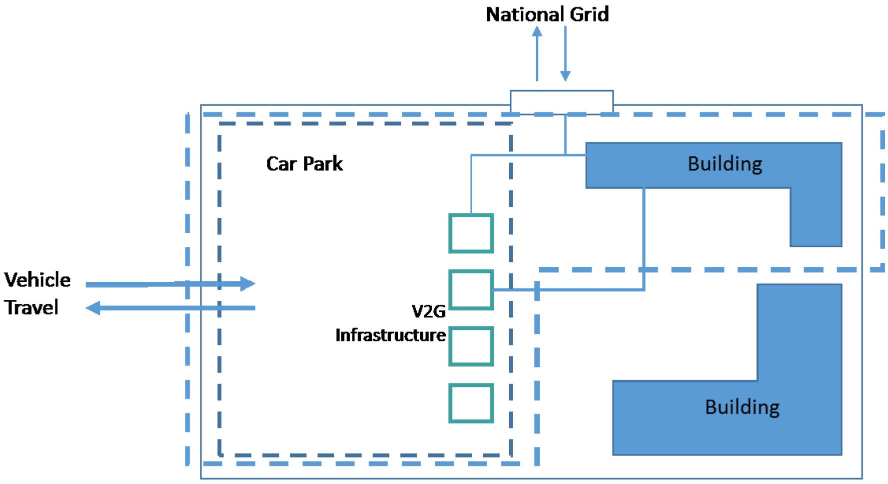


Figure 14 – Vehicle-to-Grid Feasibility Analysis Environment (V2GFAE) context diagram

3.3.2 INITIAL MODEL SPECIFICATION

This section describes the desirable functionality and basic structure of the software as specified by the author and Cenex and this forms the basis for the systems requirements outline. The V2GFAE software will evaluate a variety of scenarios relating to the use of vehicle-to-grid (V2G) with buildings, vehicles, PV and energy markets. The overall aim is to produce a report detailing the specified variables relating to technical and cost related components, and the economic viability of the case study for the evaluated scenario. The management of this is conducted through a central control strategy that links the building, vehicle, PV and market models to the scenarios for evaluation.

Control Strategy - The control strategy is the overarching model that enables the user to select which energy scenario they would like to evaluate. The control system must consider multiple actors (vehicles, energy markets, buildings and economics) to produce outputs based upon the optimisation criteria.

Vehicle Model – This simulates the vehicle information including battery capacity and usage profiles. It also provides demand profiles (charging and usage) and availability profiles (when the vehicle is available for discharging to support either the grid or a building). V2G information includes the rate of charge and discharge of the vehicle batteries and its efficiency based upon the rates of charge/ discharge.

Building Model – This includes information relating to demand profiles and economic information. The control system will use the information to establish how the building deficit should be met (if demand exceeds generation) or used (if generation exceeds demand) and income generated from V2G provision.

PV Model – This model provides a PV generation curve specific to the building being evaluated.

Market Model – This model gives information on the demand profile of STOR and the capacity market to simulate energy provision requirements of the vehicles simulated.

Cost Model – Two functions are performed by this model; a) assessment of the costs associated with the vehicles providing V2G services to either buildings or through the simulated energy markets and b) evaluating the savings made by the building through deployment of EVs with V2G. Savings to buildings are calculated with and without infrastructure costs, as well as the degradation cost to the vehicle in providing V2G services. VPP income for market trading scenarios is also calculated to establish which scenario has the greatest economic benefit to buildings or vehicle owners.

3.4 SYSTEM REQUIREMENTS AND STRUCTURE

The production of effective requirements leads to the successful creation of use cases which provide the foundation upon which the system design can built [146]. In relation to the development of requirements for the software, the Institute of Electrical and Electronic Engineers (IEEE) Computer Society [147] state *“software requirements express the needs and constraints placed on a software product that contribute to the solution of some real-world problem.”* In the context of the V2GFAE, this relates to the specification of requirements and leads to the development of software capable of simulating and responding to the complexities and interactions of the case studies.

Traditionally, three groups of requirements are generated; operational, functional and non-functional and are described by Burge Hughes Walsh [148];

“Operational Requirements (O)*; define the major purpose of the system (i.e. what it fundamentally does).*

Functional Requirements (F)*; specify what the system has to do in order to satisfy the operational requirements.*

Non-functional Requirements (NF)*; define constraints on the system. “*

3.4.1 USE CASES

Use cases are scenarios categorised by purpose in relation to the system and show the interactions between actors and the system itself, describing what the system does as opposed to how it does it [36][149]. This enables the subsequent analysis and clarification of functional and non-functional requirements [149]. Actors in the system can either be users, other elements of the system or external systems which interact in some way with the system in question [36]. The following actors have been identified within the V2GFAE; Subscriber (or user), buildings (including local PV generation), energy market and vehicles.

Operational requirements are the highest level of requirements capture and are developed from an assessment of how the system will be used and as a solution for problem solving [150]. It provides a basis from which the functional and non-functional requirements can be built upon and a reference point from which all aims of the system development must stem. For the V2GFAE software described, the operational requirement is depicted in Figure 15 and is described as follows;

"Develop a software environment in order to evaluate the investment opportunity of V2G in a local services scenario".

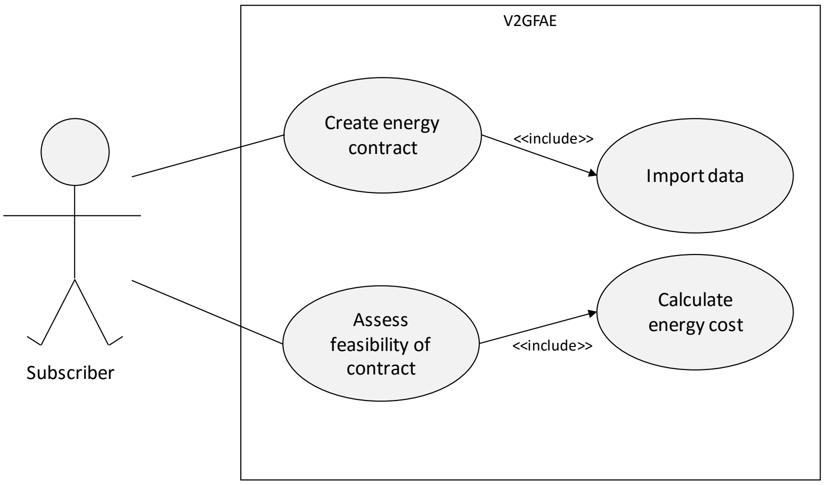


Figure 15 – Use case for V2GFAE operational requirement

The use case in Figure 15 can be described formally through a 'use case description' as given in Table 10. This describes the overall process for using the software and the expected outcome.

Table 10 – 'Evaluate Energy Scenario' Use Case Description (Adapted from [12])

Use Case Name: Create Energy Contract
Brief Description: This use case describes the setting of parameters for the overall Vehicle-to-Grid Feasibility Analysis Environment (V2GFAE) software.
Actors: Subscribers
Goal: • Successful output of suggested energy contract.
Success Measure: The input variables are selected and produce correct outputs.
Pre-conditions: • Software user has decided what system type they are evaluating. • Software user has input relevant source data. • Software is operational.
Typical Flow of Events: • Subscriber communicates intent to software operator. • Operator opens the software. • The software user knows what energy system they are evaluating. • The software presents input parameters. • The user enters input parameters. • The user loads required input data. • User selects output requirements. • Run software. • Software outputs evaluation report. • End of use case.
Assumptions: • Software user has the correct operating system and software on their computer. • Input data is available for the scenario in question to be evaluated. • The user has a prior knowledge of the software and its operation.

The following use case diagrams also have corresponding use case descriptions in Appendix A. These set out the typical flow of events within each use case to provide information for the activity diagrams. Some of the system requirements have been specified through the use case scenarios shown in Figure 15 to Figure 17. Generation of further system requirements is achieved through the next stage of the system requirements definition process; the creation of activity diagrams for each use case action.

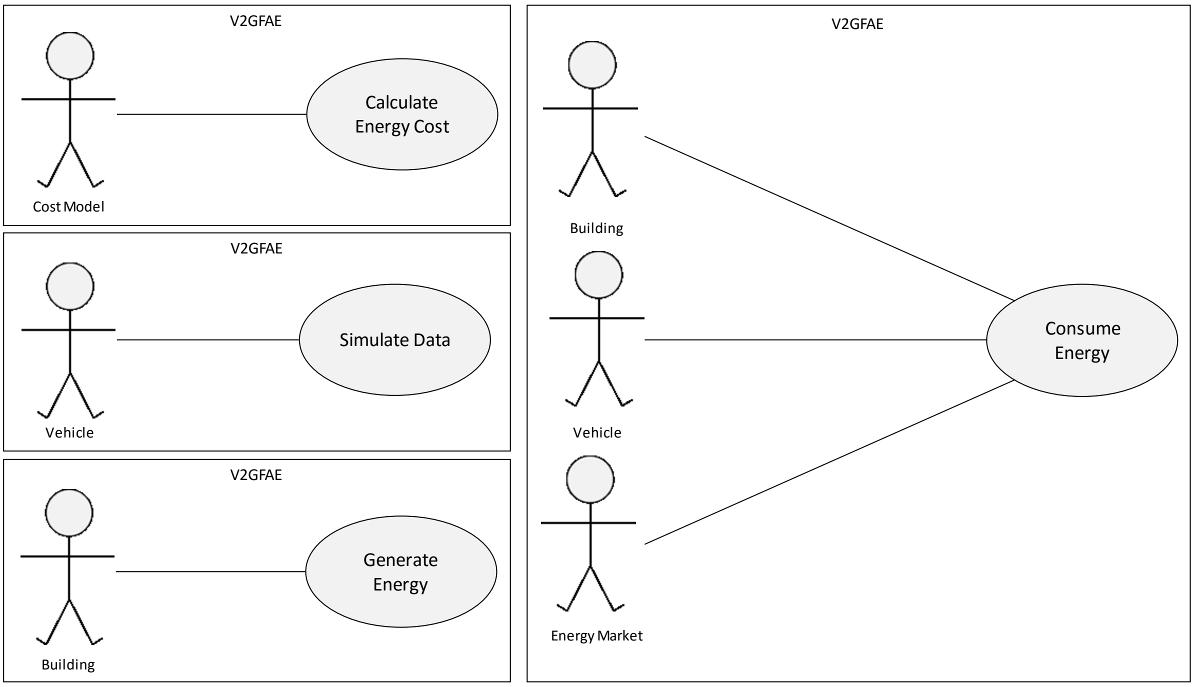


Figure 16 – Use cases for "Consume Energy", "Generate Energy", "Simulate Data" and "Calculate Energy Cost"

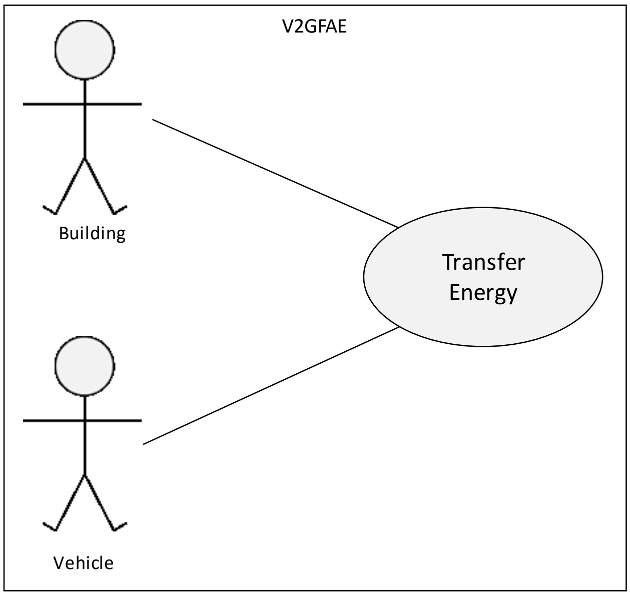
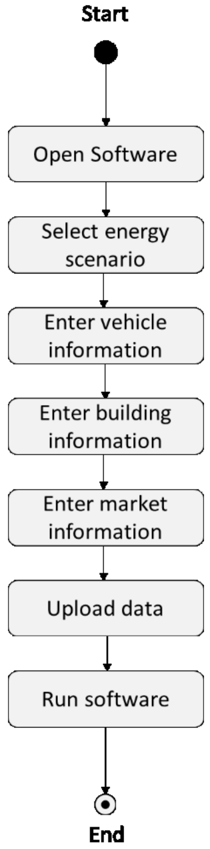


Figure 17 – Use case for "Transfer Energy"

3.4.2 ACTIVITY DIAGRAMS



Activity diagrams are useful for the identification of the processes involved within a system, the associated calculations or required system functions and describe how all activities within the system are organised [151]. They are also useful in describing the interactions between the use cases along with demonstrating any iterative behaviour within the software [2][152]. Using the information from the 'Typical Flow of Events' section within the use case descriptions, creation of simple activity flows is completed. An example of this is given in Figure 18 for the use case "Create Energy Contract". This high level description of the system provides a relatively simple view as to the functionality of the software and the required inputs and subsequent outputs.

Figure 18 – Activity Diagram for "Create Energy Contract" Use Case

One of the key uses of activity diagrams is to develop a detailed description of the system through assigning mathematical explanations and operational descriptions to these activities [151]. It is important to state the formal logic and scientific and engineering background to the software to ensure the architecture is comprehensive for the software development phase [36]. Using the activity diagrams given in Appendix A, it is possible to assign equations or control attributes to each level of the diagrams to provide a framework for building the model in a software platform. An example is given in Table 11 which depicts the operational process of the activity "Create Energy Contract".

Table 11 – "Create Energy Contract" activity description

	Activity	Description
1	Open software	**Output Format:** Software is open.
2	Select energy scenario	**Output Format:** Selection of energy scenario, as specified in Ch 4.
3	Enter vehicle information	**Output Format:** Vehicle data is loaded in specified format.
4	Enter building information	**Output Format:** Building data is loaded in specified format.
5	Enter market information	**Output Format:** Market data is loaded in specified format.
6	Upload data	**Output Format:** Data is loaded into Matlab files.
7	Run software	**Output Format:** Report summaries are produced.

Through development of the activity diagrams, the layout and structure of the software matures but there is a lack of connection between the different activity paths, which can be remedied through building a class diagram for the system.

3.4.3 CLASS DIAGRAMS

In the context of systems engineering, a class is a collection of objects within a system with very similar roles or tasks [2]. This "class" enables the objects to interact within the model without increasing the complexity of the system by allowing each object an individual interaction outside of its class [2]. The behaviour of an object is dependent upon the interactions it has within the system, along with the system state [36][2]. In the context of the V2GFAE, a change of state is dependent upon the input variables and data changing with a change in the case study of interest.

Class diagrams contain information on what is interacting as opposed to the type of interaction taking place like sequence or activity diagrams [36]. Through specification of a class diagram, an overall system view is depicted at a high level [2] [36]. However, the type of interaction is important in understanding how information is communicated across the system, with the three relationship types being association, aggregation and generalisation [36]. Associative communications demonstrate a relationship between two classes whereas aggregation describes one class owning a collection of objects belonging to another class [36]. Generalisations demonstrate inheritance from another class [36].

Based on the information obtained from the activity diagrams there are some clear systems structures developed. These are; the vehicle model, building model, PV model, cost model and market model. However, the method by which these models are assessed is through the control strategy and electricity scenarios through which the support opportunities of the EVs can be assessed. From the development of the activity diagrams and pre-existing software requirements, these can be identified as follows:

1. Building peak shaving.
2. Time of use tariff demand reduction.
3. PV peak shifting.
4. Market support.

The class diagram for the V2GFAE software is given in Figure 19. This identifies a clear structure within the software and the dominant sub-systems.

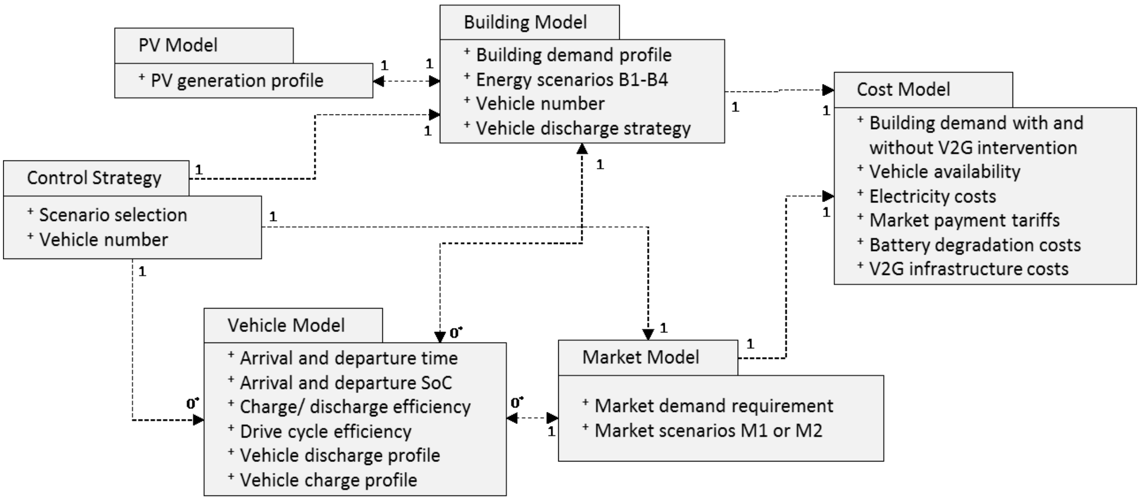


Figure 19 – Vehicle-to-grid Feasibility Analysis Environment class diagram

The control strategy enables selection of the energy scenario and number of vehicle to feed information into the building, vehicle and market models. If a PV related scenario is selected, the building model sends a control signal to the PV model, which provides generation information to the building model, to calculate the new building demand profile. The vehicle model uses the arrival and departure, journey and charge /discharge information to create a vehicle charge and discharge profile which is then provided to either the building or market model. These provide feedback to the vehicle model to indicate if the required limit has been reached or if another iteration is required. Once the conditions of the building or market model have been satisfied, the information is passed into the cost model, where financial information relating to the selected scenario is evaluated and output into a report format.

3.4.4 SEQUENCE DIAGRAMS

In order to understand the connections between each of the models within the V2GFAE, sequence diagrams are important as they show the flow of events between each of the models or 'sub-systems'. Primarily, these show the interactions between each of the systems within the software, indicating what signals or information are to be communicated and at what point in the process this occurs [36]. Figure 20 shows the sequence diagram for running a building related scenario through the V2GFAE. Initially the user will fill out the information presented to them from the user interface, which is the communicated to the relevant model via the control strategy. Once the simulation has started, the control strategy communicates with the vehicle model to commence simulation. The vehicle model then continually communicates with the building model until the objective of the scenario is reached (for example reduce building demand to a certain value), when the data is communicated to the cost model. The cost model then calculates the results of the simulation and provides them back to the user. The sequence diagrams relating to the PV and market models are given in Appendix A.

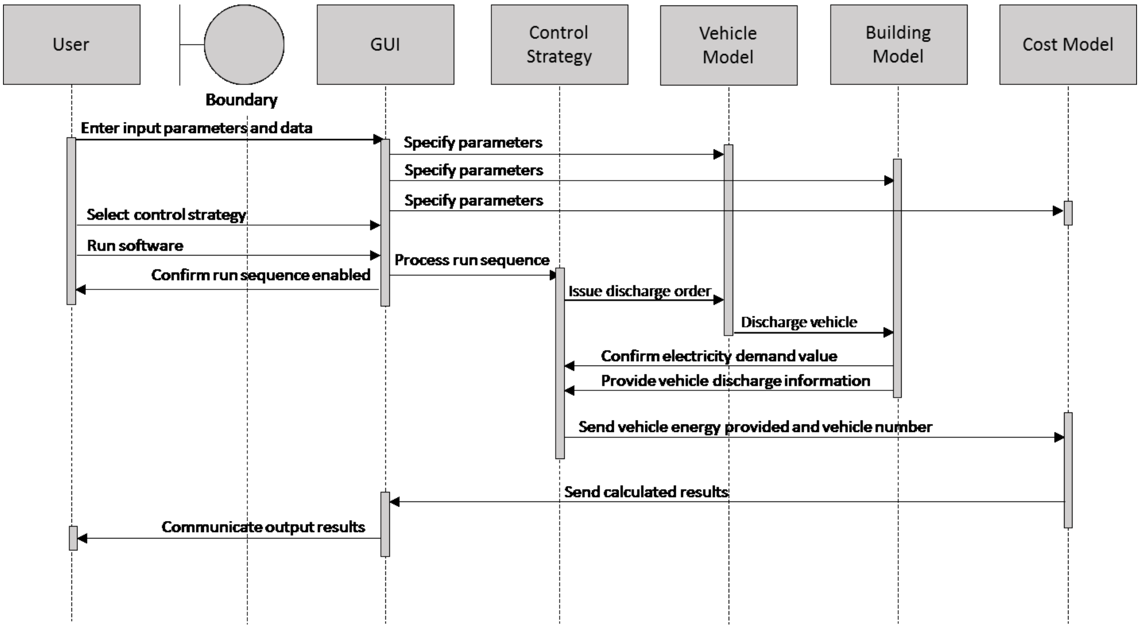


Figure 20 – Sequence diagram for building/ vehicle scenario within the V2GFAE software

3.5 CHAPTER SUMMARY

Development of the V2GFAE system engineering requirements specification through an MDA approach has involved the specification of the software functionality and formation using case study analysis, activity and class diagrams. Utilisation of these requirements tools leads to the creation of the final MDA specification and overall software formation.

The structure of the software is defined in Figure 21, with the application level operating at the top of the software, with subscribers (users) interacting with a specified interface underneath the main application layer. Data input occurs in the implementation layer, with supplier and demand interfaces representing data input for the software architecture to utilise at a software level. Cost evaluation for the supply and demand of energy interfaces with the application layer to produce energy contracts (reports) as an output from the software. Through specification of this MDA diagram for the V2GFAE software the final requirements definition is identified in Table 12.

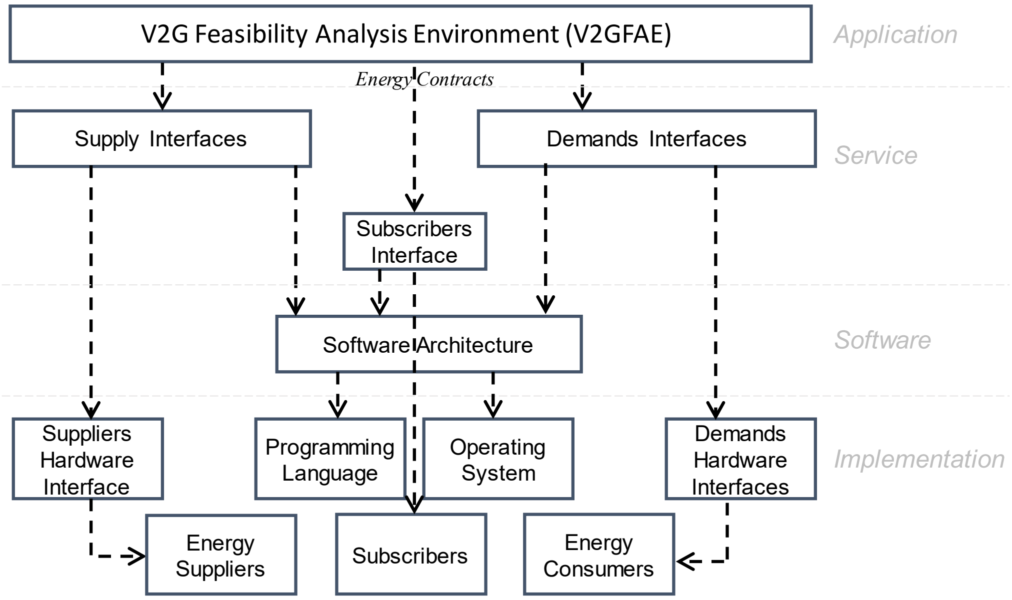


Figure 21 – MDA view of V2GFAE software

Development of the software architecture through a model driven approach has led to the creation of a high level design detail and system requirements specification. The usefulness of this design is in the modular nature of the software, using a variety of models to integrate to form the overall V2GFAE system, allowing for easy creation and manipulation of the software and subsequent modifications. The design of the MDA for the V2GFAE in Figure 21 also follows a bottom up formation, further simplifying the creation of the software through modulation. This is supported by the class diagram that defines the various communications pathways and associations between each of the model classes. Through this MDA approach to system design, the requirements have been clearly defined as per the stakeholder's initial specification and the software build process specified through activity diagrams.

Table 12 – Final Requirements Definition

	Requirement	**Type**
R1	Develop a software environment in order to evaluate the investment opportunity of V2G in a local services scenario.	O
R2	High resolution simulation of vehicle arrival and departure information from real-world data to gain an intrinsic understanding of vehicle use profiles.	F
R3	Impact of increased battery cycling on the economic viability of V2G for individual vehicles.	F
R4	Use Manchester Science Park as a case study.	F
R5	Create the software environment in Matlab.	NF
R6	Evaluate economic viability of case studies through defined and built-in scenarios.	F
R7	Evaluate any case study with a combination of buildings/ vehicles/ PV and market demand.	F
R8	Understand the sensitivities around electricity tariffs and pricing structures.	F
R9	Understand the sensitivities around infrastructure pricing.	F
R10	Understand the impact of vehicle usage profiles on storage provision.	F
R11	Evaluate the economics of case studies for different energy scenarios.	F
R12	Evaluate using EVs to provide peak saving for buildings.	F
R13	Evaluate using EVs to provide TOUT reduction.	F
R14	Evaluate the use of EVs for load shifting in buildings with PV.	F
R15	Understand the economic benefits to buildings in utilising EVs with V2G.	F
R16	Understand the economic benefits to EVs in providing electricity to buildings through V2G.	F
R17	Building to consume energy.	F
R18	Vehicle to consume energy.	F
R19	Electricity grid to consume energy.	F
R20	Building to generate energy.	F
R21	Vehicle to transfer energy.	F
R22	Building to transfer energy.	F
R23	Vehicle to simulate data.	F
R24	Cost model to calculate energy cost	F
R25	Control strategy to specify system of interest (Wider Energy System or Local Energy System).	F
R26	Software outputs – cost profiles for vehicles and buildings.	F
R27	½ hour time step.	NF
R28	Compatible with excel, csv and txt for file import.	NF
R29	Easy GUI for variable input and editing.	NF
R30	Simulate STOR and capacity market models.	F
R31	Simulate for daily profiles.	F
R32	Ability to select a variety of scenarios for analysis independently.	F
R33	Variable charge/ discharge efficiency depending upon rate of energy transfer.	F
R34	Number of vehicles is variables within the software.	F
R35	Output report to summarise the results from the analysis.	F
R36	Easy to maintain and update.	NF
R37	Reliability – the software is reliable.	NF

CHAPTER FOUR

SOFTWARE DEVELOPMENT

4.1 INTRODUCTION

Creation of the Vehicle-to-Grid Feasibility Analysis Environment (V2GFAE) is the next developmental stage of the systems engineering 'vee', as given in Figure 22. Following the creation of the system architecture in Chapter 3, identification of the software build and simulation methods is necessary to satisfy the requirements generated through the SE process.

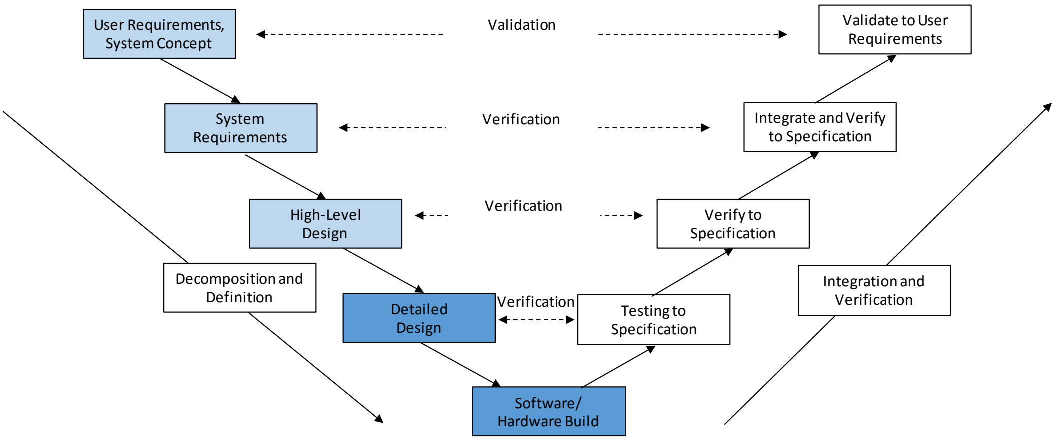


Figure 22 – Design and Build Phase of Systems Engineering 'Vee' Process

The modelling process follows the structure set out by the architecture framework specified in Chapter 3, developing each of the system use cases in turn through the approach stipulated in the activity diagram descriptions. The software is built up from the vehicle model using a bottom up approach, simulating vehicles arriving and departing from the location specified by the data set or variables entered into the V2GFAE.

4.2 MODELLING AND SIMULATION APPROACH

Several approaches were considered for the development of the software to create the V2GFAE including heuristic analysis, stochastic modelling, Monte Carlo (MC), agent based modelling (ABM), discrete event simulation and system dynamics (SD). Example uses of these approaches are discussed in Chapter 2, however the final approach was influenced by the requirements definition specified in Chapter 3. The following are identified as directly influencing the method used in creating the software;

R1 – Develop a software environment in order to evaluate the investment opportunity of V2G in a local energy services scenario.

R5 – Create the software environment in Matlab.

R27 – Conduct modelling using a half-hour time step.

R28 – Compatible with .xls, .csv and .txt for file import.

From these requirements, a Monte Carlo based approach was chosen due to its stochastic, time-series based modelling methodology. Vehicle information including arrival and departure times and battery state of charge are sampled from randomly generated, beta distributed variables based on imported usage data. A beta distribution was chosen as it best fit the data used to build the basic software operation.

Each of the activity diagram parameters specified in Chapter 3 have corresponding equations within this chapter. This provides a comprehensive overview as to the structure and formation of the software, including excerpts of code to demonstrate the application of the equations and example outputs. As specified in Chapter 3, the software is formed of a series of connected models; vehicle, building, market, PV and cost model. The software description begins with the vehicle model, as this is the most complex within the software, where an MC based approach is used to generate vehicle information from imported data. The bottom-up design approach followed for software creation is built up from this model, as demonstrated in Figure 23.

The chapter then discusses the building and PV models, with the first four scenarios developed that relate the outputs from the vehicle model with the building and /or PV. These calculate the impact of vehicle numbers on the V2G support opportunities for the building, with and without PV and based on a variety of electricity charging structures. The market model simulates the call periods for Short Term Operating Reserve (STOR) and the Capacity Market. The outputs from these models are fed into the cost model that explores the financial benefits of V2G to both the vehicles and buildings. The results from this analysis are provided through an output report at the end of the simulation to enable software users to make an informed decision as to the economic suitability of V2G within their energy scenario. An example of this report is given in Appendix B.

For each output calculated within the software described here, the format of the output is described in either a table or list format. For single variables, this is given as ‘Output Variable Name’, followed by the name in list form. For outputs with multiple values, such as in the form of a matrix or vector, this is specified in a table with the following possible headings; Output Variable Name, Size, Class and Range. A description of what each of these means is given in Table 13.

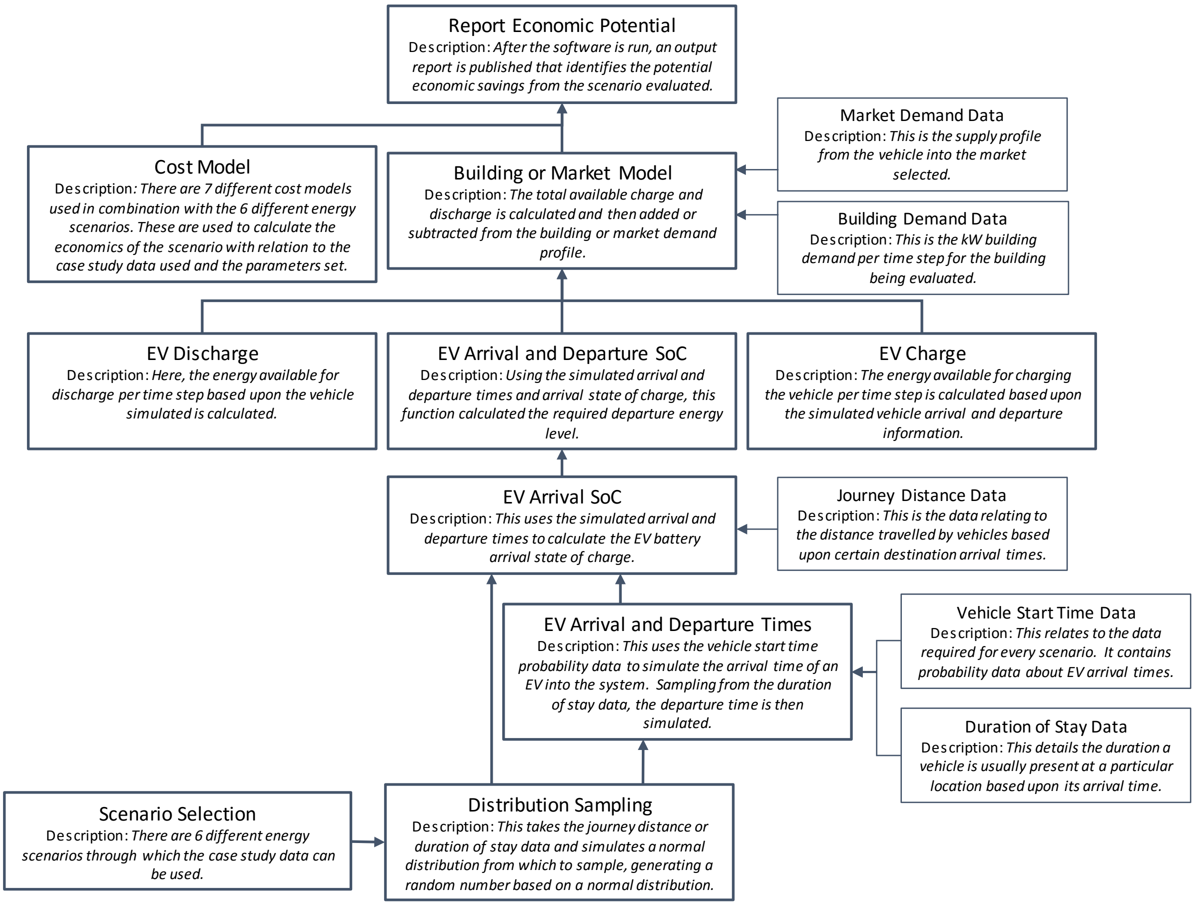


Figure 23 – Demonstration of the bottom up approach to software structure

Table 13 – Output format descriptions

Name	**Description**
Size	This refers to the dimensions of the variable within the Matlab workspace. AA x EE for example, means AA number of rows with EE number of columns. Most variables within this analysis will have 48 rows as there are 48 ½-hour time steps in a 24-hour period.
Class	This refers to the type of variable within the Matlab environment. Where the variable size is larger than a 1 x 1 matrix the class will be 'double' which refers to the precision of the data returned by the software.
Range	Some variables require a range to be specified, for example where probabilities are involved. This simply refers to the values the variable must stay within.

4.3 VEHICLE MODEL

Referring back to the context diagram (Figure 14), the identification of vehicle arrival and departure times in and out of the system of interest is key to the success of the vehicle model. This model imitates this behaviour through simulating vehicle arrival and departure times, state of charge (SoC) and EV energy storage and discharge availability. This is performed through MC based analysis, using a random number generation approach to estimate the probability of a vehicle arriving in a particular time step (set at 30 minutes for all simulations). This arrival information is then fed into another probability model to calculate the length of time the vehicle will stay within the system of interest, leading to the estimated departure time. To calculate the arrival and departure battery state of charge the model considers the distance travelled to and from the system of interest by the vehicle. Using the arrival and departure times the model samples from normal distributions to generate estimated distance travelled. This information is then used to calculate the energy consumption per journey and therefore the energy available for discharge or storage capacity available for the duration of the vehicles stay. This process allows for a variety of vehicle related data to be used for simulation, so long as information is available relating to arrival and departure times and distance travelled by the vehicle. More information on the exact data format is specified in Section 4.3.1. Travel survey data can therefore be used as a data source required, as well as data relating to journey information from ICE vehicles.

The outputs from the vehicle model are then fed into either the building, PV, market or cost model to calculate a vehicles suitability for either energy storage or discharge. The model is based on a series of equations and iteration sequences that allow multiple vehicles to be sampled and simulated using a stochastic modelling method. The required inputs and outputs for the vehicle model are expressed in Figure 24.

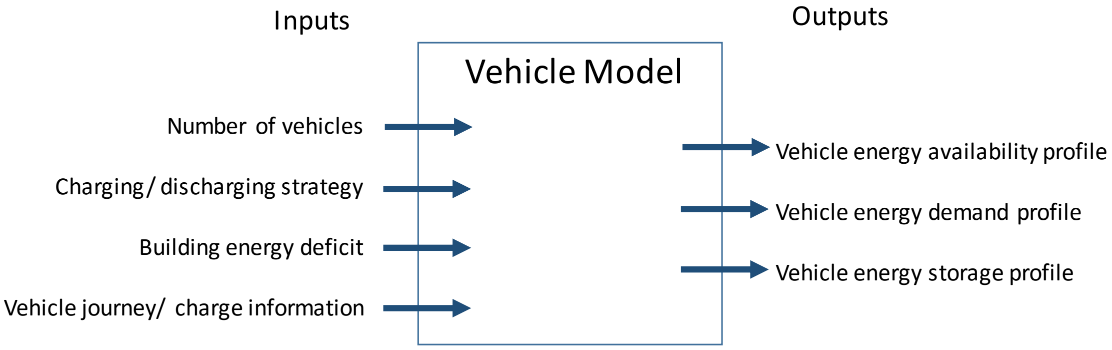


Figure 24 – Vehicle model inputs and outputs

4.3.1 Simulate Vehicle Data

Travel data forms the basis for the vehicle model and is built upon vehicle input data from which arrival and departure times and state of charge can be calculated using a transition probability matrix (TPM). The TPM identifies the probability of a vehicle arriving at a particular time and the model then simulates random numbers and allocates these to the TPM to estimate the vehicle's time of arrival.

A. Import vehicle arrival time data

The data input format for the vehicle arrival information is given in Table 14, which gives an example of the import script and file name.

Output Format: Probability of vehicle arriving vs. time step.

Table 14 – Output variable name and format requirement for vehicle arrival time data

Output Variable Name	Size	Class	Range
Prob1	48 x 1	double	0-100

Process:

1. Calculate number of vehicle arrivals per time step and probability of arrival. This can be completed in Matlab or another data editor. In the example given in Figure 25 the probability is already imported as the data has been edited in MS Excel. The probabilities were calculated as follows;

$$P(Arrival) = \frac{Number\ of\ events\ per\ time\ step}{Total\ number\ of\ events} \tag{2}$$

```
%% Load vehicle arrival and departure time telemetry data and
generate probability matrix from dataset
% Prob1 is the probability matrix for data set
[ndata1, text1, alldata1] = xlsread('Charge_Energy_Pool_v1.xlsx',
'Start_Times_30'); %Import data from file
Charge_Energy_Individual
Prob= alldata1(:,3);
Prob(1,:)=[];
Prob1 = cell2mat(Prob);
Prob1(isnan(Prob1(:,1)),:)=[] ; % remove NaN from matrix
```

Figure 25 – Import vehicle telemetry data relating to start time of charge

2. Specify correct output format. The output format for this probability is specified in Table 14, with the range between 0 and 100. The size corresponds a probability to each time step, which is 48, one for each half-hour.

B. Import duration of stay data

This data is filtered by time of arrival. The data should be separated into relevant bins, with each bin corresponding to an hour (see Table 15). If a journey commenced within that hour-long bin, the corresponding duration of the journey (in minutes) is specified within that bin. For example, in Table 15 the first journey specified in the 01:30 – 02:29 bin lasted for 45 minutes.

Table 15 – Example data input format for 'Duration of Stay' and 'Journey Distance'

00:30-01:29	01:30-02:29	02:30-03:29	03:30-04:29	etc
29	45	44	79	X
12	1	43	2	Y
	58	66		Z
		12		Z

Output Format: 24 bins relating to hour of arrival with duration of stay underneath.

Table 16 – Output variable name and format requirement for vehicle duration of stay

Output Variable Name	Size	Class
TimeD	n x 24	double

Process:

Each column will potentially have a different number of variables underneath, depending upon the number of vehicle arrivals that occurred within that hour period. The data can be arranged using any data editor, including Matlab and Figure 26 demonstrates an example import script for an MS Excel based data set.

```
% Load vehicle 'duration of stay' data and probability
distributions using function
% Loads all data to be used to create prob curves to sample from
[ndata, text, alldata] =
xlsread('Charge_Energy_Pool_v1.xlsx','Work_Time_Weekd');
alldata(1,:)= []; % Delete first line of each variable
TimeD= cell2mat(alldata); % Cell to Double
Time00 = TimeD(:,1); % Convert from alldata to individual
variables
Time01 = TimeD(:,2);
Time02 = TimeD(:,3);
% etc…
```

Figure 26 – Import vehicle duration of stay data

C. Import journey distance data

This data format is exactly the same as with Part B - Import duration of stay data, the only difference being the output variable name and data included.

Output Format: 24 bins relating to hour of arrival with distance travelled underneath (Table 17).

Table 17 – Output variable name and format requirement for journey distance

Output Variable Name	Size	Class
TimeJ	n x 24	double

D. Simulate vehicle arrival and departure times

Simulating a vehicle arrival time is a case of randomly generating numbers and comparing them to the arrival probability dataset, such as with a TPM. If the generated random number is less than or equal to the probability, the TPM assigns a value of 1, identifying the arrival time. Using the imported data relating to duration of stay for the vehicles (part B), beta distributions are created for each hour of the day. Based on the simulated arrival time, the model samples from the appropriate normal distribution to allocate a duration of stay for the vehicle. From this, the departure time can then be calculated.

Output Format: Two matrices with – 1) arrival time vs. time step and 2) departure time vs. time step.

Table 18 – Output format for simulated vehicle arrival and departure times

Output Variable Name	Size	Class	Column 1
ValueofStart_Time	n x 1	double	Time Step
ValueofEnd_Time	n x 1	double	

Process:

1. Generate 48 random numbers between 0 and 1, assign as 'x' with probability function.

$$P_x(x) = P(X = x) \quad (0 \le x \le \ 100)[153] \tag{3}$$

Where 'x' is a 48x1 matrix with a range of 0 and 100.

2. Compare to probability of arrival using transition probability matrix.

If $M = x \le Probability\ of\ Arrival$, M = 1, else M = 0.

(4)

Where 'M' is a 48x1 matrix with a range of 0 and 1.

3. Calculate which 'duration of stay' distribution to sample from based on arrival time. This is shown in Figure 27 where the output name is 'Duration'.

```
    if Start_Interval >= 02 & Start_Interval< 04;          % Use
start time to identify higher order probability to pull from
        Duration = Time01_NORM * 24;
    elseif Start_Interval >= 04 & Start_Interval<06;          %
If between XX and XX allocate to relevant duration distribution
        Duration = Time02_NORM * 24;
% etc…
```

Figure 27 – Sample from loop to simulate vehicle arrival and departure times

4. Generate a normal distribution for vehicle ‘duration of stay’ for the selected time period using mean and standard deviation. These distributions are then sampled from to identify how long the vehicle was present within the system using a random number generated from the distribution. The code to perform this is given in Figure 28.

$$mean(\mu) = \frac{\sum x}{N}$$

(5)

Where; x is the observed value and N is the number of values in the set and the sampled standard deviation is;

$$\sigma \;\; = \sqrt{\frac{\sum(x \; - \; \bar{x})^2}{N-1}}$$

(6)

This produces a normal distribution with probability density function;

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma^2)}$$

(7) [154]

```
% Sample from normal distribution for journey distance
n = 1; % Number of Vehicles
Time00J_NORM = normrnd(Time00J_MU,Time00J_SD,[n 1]); %Produced
'n' random numbers sampled from the distribution curve
Time01J_NORM = normrnd(Time01J_MU,Time01J_SD,[n 1]);
% etc…
```

Figure 28 – Random number generated based on normal distribution

5. Calculate end time;

$$End\ Time = Start\ Time + Duration$$

(8)

Where End Time is End_Time, Start Time is Start_Interval and Duration is Duration. To end the simulation, the following if loop is added;

$$If\ end\ time\ \geq 48$$
$$STOP$$

If there are multiple start times, this process is repeated until all start times have a corresponding end time.

The result of running this code within the model is the production of two matrices, one displaying all of the vehicle arrival times and one with the vehicle departure times. An example of a graphical representation of this is given in Figure 29 for an example vehicle simulated over a 24-hour period.

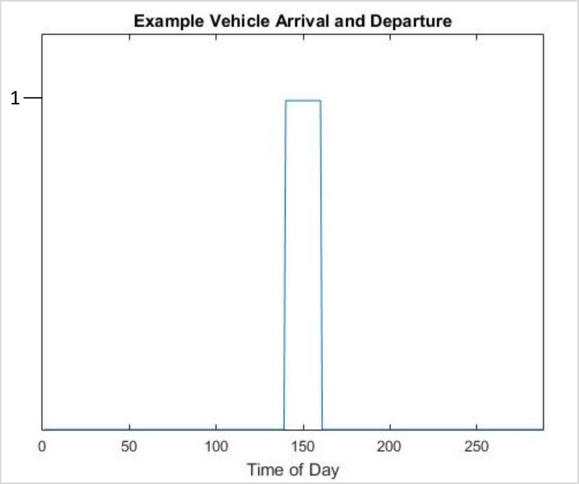


Figure 29 – Example vehicle arrival and departure signal

E. Simulate vehicle arrival and departure battery state of charge

To calculate the energy level in the vehicle battery on arrival and the subsequent required departure level, a 'while' loop is used to perform a similar iteration as the previous calculation in Figure 27. Using the imported journey information, distributions are created and sampled from to assign a journey distance to an arrival and departure time. These values are then fed into the drive cycle efficiency equation to establish the amount of energy used per journey (calculated using Artemis values for the vehicle). These indicate the amount of energy consumed per 100km (kWh/100km) based on the drive type (urban, road or motorway). To calculate the energy required by the vehicle to make a return journey the vehicle model follows the same procedure. However, as the departure distance is an unknown variable, a 'buffer' must be set that ensures longer journeys can be made without the EV requiring additional charging (for example, 40%).

Output Format: Produce two matrices with battery energy value (kWh) vs. time step for start and end times.

Table 19 – Output format for simulated vehicle arrival and departure times

Output Variable Name	Size	Class	Column 1	Column 2
Battery_Capacity_Arrival	n x 2	double	Time Step	Capacity Level
Battery_Capacity_Depart	n x 2	double		

Process:

1. Set maximum battery capacity, battery buffer (percentage battery capacity cannot drop below) and Artemis values. See Table 20 for output variables.

Table 20 – Set vehicle parameters including capacity, buffer and Artemis values

Output Variable Name	Description	Units
Battery_Capacity	Maximum battery capacity	kWh
Battery_Buffer	Percentage battery cannot discharge below	%
Art_Urban	Artemis urban	kWh/100km
Art_Road	Artemis road	kWh/100km
Art_Motorway	Artemis motorway	kWh/100km

2. Create normal distribution from vehicle journey distance for each hour (as per D).

3. Calculate which distribution to sample from based upon arrival time (as per D).

4. Sample from distribution (as per D).

5. Loop until all arrival times have a corresponding journey distance.

6. Calculate drive cycle efficiency for each journey using either an average, urban, road or motorway Artemis value (any value can be selected from within the software);

$$Drive\ Cycle\ Efficiency = \frac{Artemis\ Value}{100}\ x\ Journey\ Distance \tag{9}$$

$$Average\ Artemis\ Value = \frac{Art_{Urban} + Art_{road} + Art_{Motorway}}{3} \tag{10}$$

7. Calculate arrival battery energy value (first journey of the day);

$$Arrival\ Battery = Maximum\ Battery\ Capacity - Drive\ Cycle\ Efficiency \tag{11}$$

8. Calculate departure battery capacity;

$$\begin{gathered} Departure\ Battery = Departure\ Drive\ Cycle\ Efficiency \\ +(Maximum\ Battery\ Capacity\ x\ Battery\ Buffer) \end{gathered} \tag{12}$$

9. If there are multiple journeys made by the same vehicle in 24 hours, the subsequent arrival battery capacity is calculated as follows;

$$Arrival\ Battery\ Subsequent = Departure\ Battery - Arrival\ Drive\ Cycle\ Efficiency \tag{13}$$

F. Calculate energy available between arrival and departure

This is a simple requirement to calculate the energy available between the arrival and departure of the vehicle.

Output Format: kWh vs. time step.

Table 21 – Output format for simulated vehicle energy availability

Output Variable Name	Size	Class
Total_V2G_Energy_Supplied	48x1	double

Process:

For each arrival and departure journey conducted by the vehicle over the 24-hour period simulated, the following calculation is performed to establish the energy available within the vehicle for discharge when the vehicle is within the system.

$$Energy\ Available\ = Arrival\ Battery - Departure\ Battery \tag{14}$$

G. Calculate energy required for charging

This calculates the deficit battery capacity of the vehicle to establish the storage capacity of the vehicle when it first arrives into the system.

Output Format: kWh vs. time step.

Table 22 – Output format for simulated vehicle charge provision

Output Variable Name	Size	Class
Total_Charge_Provision_Sum	48x1	double

Process:

For each arrival and departure conducted by the vehicle over the 24-hour period simulated, the following calculation is performed to establish the capacity available within the vehicle for storage provision when the vehicle is within the system.

$$\text{Available Storage Capacity} = \text{Maximum Battery Capacity} - \text{Arrival Battery} \tag{15}$$

4.3.2 CALCULATE VEHICLE ENERGY CONSUMPTION

This section details the calculations required to charge the vehicle battery. This is based on a battery model that takes the rate of charge and battery energy level and calculates the charge/ discharge efficiency of the battery. This is then used to calculate the charging of the vehicle per time step.

This is supported by a battery model supplied by Warwick Manufacturing Group (WMG) based on data for a 2011 Nissan Leaf. The Simulink model uses input data relating to capacitance, open-circuit voltage, rate of charge, rate of discharge and state of charge to calculate the new state of charge per time step for charging. Three inputs; initial state of charge (%), ambient temperature (^{o}C) and power

(W) are specified by the model users to provide two outputs; charge efficiency per time step (%) and new state of charge (%).

A. Calculate charge efficiency

Output Format: Percentage (%).

Output Variable Name: eta

Process:

1. Calculate charge (or discharge) efficiency per half-hour time step.

$$\eta = \frac{OCV - V}{OCV} \tag{16}$$

Where η is charge efficiency, OCV is open-circuit voltage and V is voltage.

B. Calculate state of charge per time step

Output Format: %.

Output Variable Name: SoC0

Process:

1. Calculate new state of charge (SoC) per half-hour time step.

$$SoC(t) = SoC(0) - \frac{1}{C_{bat}} \int I.dt \tag{17}$$

Where SoC is state of charge and C_{bat} is battery capacitance.

C. Calculate battery capacity per time step

Output Format: kWh.

Output Variable Name: Charge_Value_BC

Process:

1. Calculate total time available.

$$Time\ Available = End\ Time - Current\ Time \tag{18}$$

2. Calculate total storage capacity available.

$$Storage\ Available = Maximum\ kWh - \ Current\ kWh \tag{19}$$

3. Calculate the charge value (Charge_Value_BC).

$$Charge\ Value\ (kWh) = \frac{Storage\ Available\ x\ \eta}{Time\ Available}$$

(20)

4. Calculate new battery energy level (kWh).

$$New_{BC} = Start\ kWh - Charge\ Value$$

(21)

4.3.3 TRANSFER VEHICLE ENERGY

The discharge of available vehicle energy could follow two possible approaches. Both are discussed in this section, with the first discharging the battery as soon as the vehicle is plugged into the system (un-managed strategy). This produces a clustered, un-managed discharge profile, however the second provides an even discharge throughout the duration of the vehicles stay which demonstrates a managed strategy.

A. Calculate discharge efficiency

See Section 4.3.2 - A. Calculate charge efficiency

Approach 1 – Maximum Discharge

This approach involves setting a fixed discharge energy transfer value and discharging all the vehicles at the same rate as soon as they are plugged in. This produces a clustered discharge profile as depicted in Figure 30 which does not allow for controllable energy management.

A. Calculate energy available per time step

This calculates the discharge level as a fixed value.

Output Format: kWh vs. time step.

Table 23 – Output format for energy available per time step

Output Variable Name	Size	Class
Discharge_Value_BC	48x1	double

Process:

1. Time required to discharge the full availability is;

$$Time\ Required\ Discharge = \frac{Energy\ Available}{Rate\ of\ Discharge\ x\ Discharge\ Efficiency}$$

(22)

2. The discharging of the vehicle happens in a loop. For each time step the vehicle is present, the vehicle is discharged at the following rate which equals the energy available per time step;

$$Final\ Discharge\ Rate = Rate\ of\ Discharge\ x\ Discharge\ Efficiency \tag{23}$$

The energy level of the vehicle is therefore a cumulative decrease, with each time step decreasing the energy level as follows until either the vehicle is due to leave the system or the departure battery capacity has been reached (based on stop function within calculation loop);

$$Next\ Step\ Discharge = \ Current\ Charge - (Rate\ of\ Discharge\ x\ Discharge\ Efficiency) \tag{24}$$

An example output from this type of discharging strategy of 25 vehicles is given in Figure 30. The form of the energy discharge is quite irregular and in two distinctive blocks due to immediately discharging the vehicles upon arrival. For building or market support it would be advisable to explore the option of a more managed discharging strategy to produce an even profile throughout the vehicles duration on-site that emulates a managed charging strategy. The profile of the graph is as a result of some of the vehicles simulated making two trips during the day, with the dip in the middle as a result of the vehicles being used.

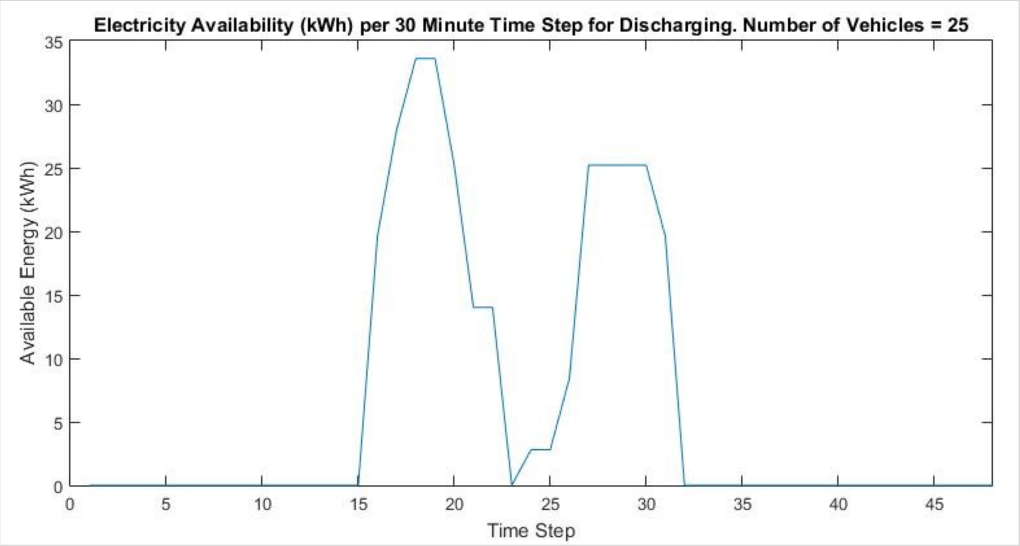


Figure 30 – Example V2G energy availability profile with discharging availability

Approach 2 – Constant Discharge

This is a much simpler approach to vehicle discharging than using a fixed rate of discharge. Through this approach, the total energy available within the vehicle is divided across the total time available, generating a constant discharge rate for each vehicle. This approach provides a much smoother discharge profile for the vehicles (see Figure 32) which when applied to building profiles, ensures peak shaving occurs smoothly. Within the software this approach closely replicates a managed strategy where vehicle discharging is staggered to meet demand. This is exemplified in Figure 31, where the first impact demonstrates the strategy employed through this approach, and the second shows a managed charging strategy. It can be deduced that through aggregating the energy available within all of the vehicles, the output of the discharge profiles are the same or similar to that of a more complex, managed strategy.

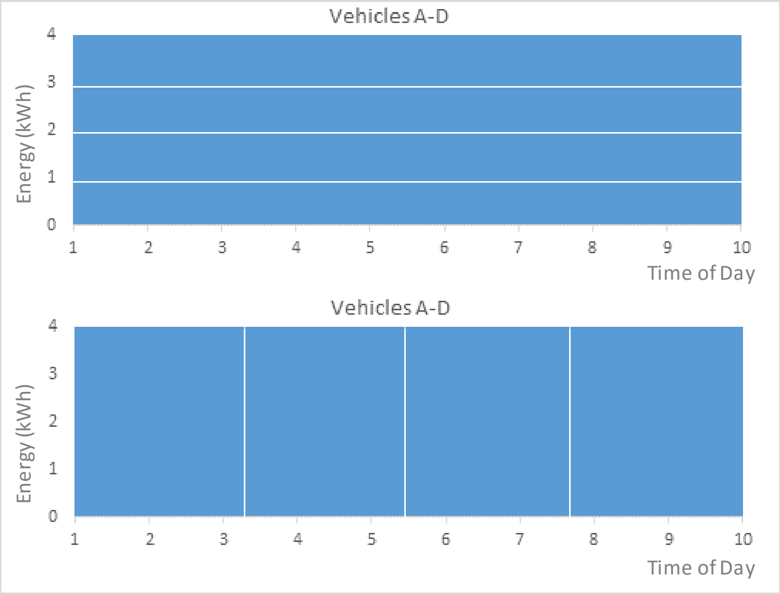


Figure 31 – Example discharge comparison for vehicle management strategies

A. Calculate discharge efficiency

See Section 4.3.2 - A. Calculate charge efficiency

B. Calculate state of charge per time step

See Section 4.3.2 - B. Calculate state of charge per time step

C. Calculate energy available per time step

Output Format: kWh.

Output Variable Name: Discharge_Value_BC

Process:

1. Calculate total time available.

$$Time\ Available = End\ Time - Current\ Time \tag{25}$$

2. Calculate total energy available.

$$Energy\ Available = Arrival\ kWh - \ Current\ kWh \tag{26}$$

3. Calculate the discharge value (Discharge_Value_BC).

$$Discharge\ Value\ (kWh) = \frac{Energy\ Available\ x\ \ \eta}{Time\ Available} \tag{27}$$

4. Calculate new battery energy level (kWh).

$$New_{BC} = Start\ kWh - Discharge\ Value \tag{28}$$

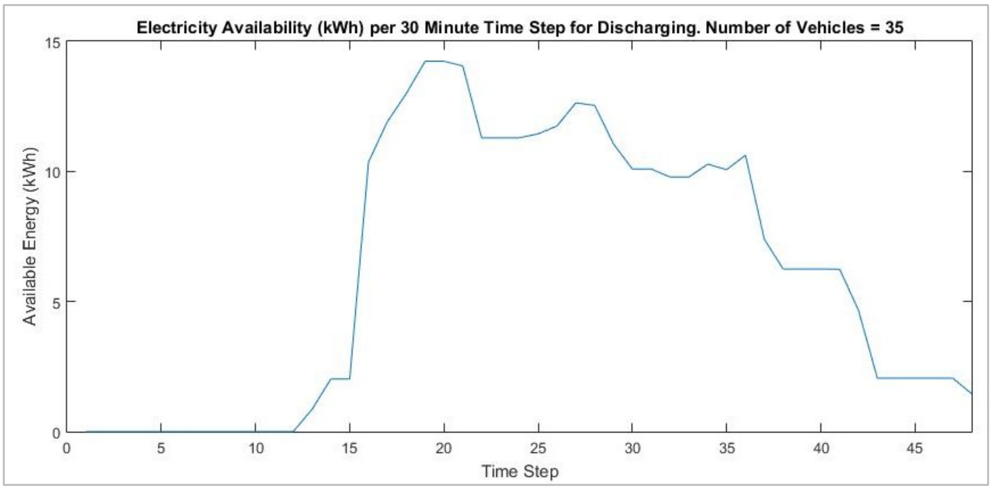


Figure 32 – Output from calculation of energy available from Approach 2

Before moving onto the building model to calculate the charging and discharging requirements of the vehicles with relation to building demand, it is first necessary to describe the PV model and the impact this has on the building energy scenarios.

4.4 PV MODEL

This model creates a PV profile from generation data for use in the PV building models in the next section. The data requirements are shown in Figure 33.

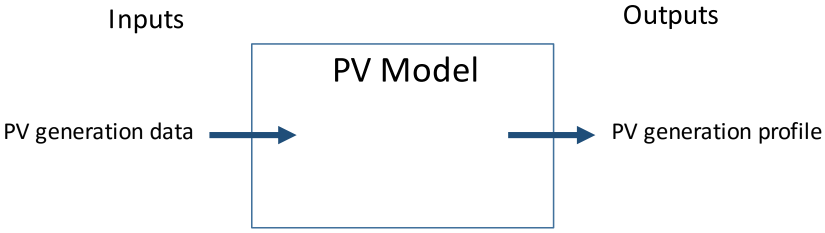


Figure 33 – PV Model Inputs and Outputs

4.4.1 GENERATE PV ENERGY

The PV generation model is relatively simple as it uses externally created PV generation data to create average half hourly PV generation data for the building or buildings being evaluated.

A. Import PV generation data

The method for importing the PV data can vary depending upon the input data type, however the output format must be in the same format as is specified in Table 24.

Output Format: Half- hourly average generation data vs. time step.

Table 24 – Required PV Generation Data Format

Output Variable Name	Size	Class
PV_Total_Daily_Mean	48x1	double

The method by which the data can be imported is dependent upon the format in which the data is held, meaning data could be monthly, weekly or daily depending on the analysis required by the software user.

4.5 BUILDING MODEL

This model forms the basis for the four energy scenarios built into the V2GFAE in which energy from the vehicles is used to supply buildings. The input and output requirements have been described in Figure 34. Using the structure developed through the model driven architecture, the building model is formed of two main elements; a) consumption and b) transfer of energy as detailed in the next section.

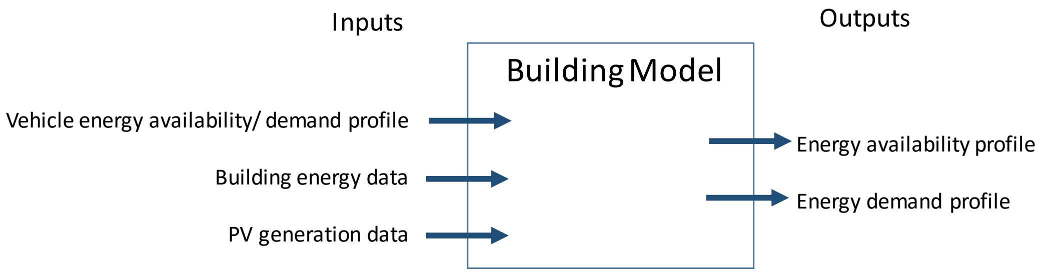


Figure 34 – Building Model Inputs and Outputs

4.5.1 CONSUME BUILDING ENERGY

The data imported into the building model can vary depending on the building type being explored, the number of buildings or the data type, for example average yearly, monthly or weekly. However, the format of the final data output must be consistent with the format expressed in Table 25. Only one building data set can be evaluated at a time through the model, however through running the model multiple times a variety of buildings can be evaluated and compared.

A. Import building demand data

Output Format: kW vs. time step.

Table 25 – Building demand data format

Output Variable Name	Size	Class
Aggregated_Yearly_Building_Demand	48x1	double

The method for importing the data can vary depending upon the original data format, however an example import process from an excel file is given in Figure 35.

Based on this import format, the final output variable is calculated using the mean demand for each half hour period.

```
% Import the data
  [~, ~, raw] =
xlsread('C:\Users\Becky\Dropbox\Matlab\All_Buildings_Formatted.xl
sx','Combined_Mean','A2:CA49');

  %% Create output variable
  data = reshape([raw{:}],size(raw));

  %% Allocate imported array to column variable names
  Time = data(:,1);
  Enterprise_Jan_Mean = data(:,2);
  Enterprise_Feb_Mean = data(:,3);
% etc
```

Figure 35 – Import Building Demand Data

4.5.2 TRANSFER BUILDING ENERGY

The first two energy scenarios described here involve the discharging of EV stored energy into the building on an any time and triggered basis (see Table 26). Scenario B1 looks at discharging battery storage from the EVs at any point during the day so long as the vehicle is present within the system, has energy available and the building has a positive demand profile. Scenario B2 explores the impact differing prices of time of use tariffs (TOUT) has on the management of the EV discharging model. Through this scenario the vehicles are only able to discharge during the allowable times set by the tariff. The final two building scenarios explore the addition of PV generation on-site, with a negative building demand as a result of excessive PV charging causing the vehicles to charge. The market scenarios – M1 and M2 – explore the provision of energy from vehicles for STOR and the capacity market respectively.

There are two options for vehicle numbers within the model, hence a requirement for four scenarios with two discharge types. The first specifies the number of vehicles and provides discharging strategies based on these numbers, whilst the second calculates the number of vehicles required to meet the target building demand level.

Table 26 – Scenario summary table

Scenario	**Scenario Description**
B1	Building demand, no PV, vehicles discharge as and when available and required to provide peak shaving to the building. Vehicle number is specified.
B1.1	Building demand, no PV, vehicles discharge as and when available and required to provide peak shaving to the building. Vehicle number is calculated.
B2	Building demand, no PV, vehicles discharge when available within the specified time of use tariff. Vehicle number is specified.
B2.1	Building demand, no PV, vehicles discharge when available within the specified time of use tariff. Vehicle number is calculated.
B3	Building demand, PV generation, vehicles charge when available and if there is an excess of PV generation. They discharge as and when available and required to provide peak shaving to the building. Vehicle number is specified.
B3.1	Building demand, PV generation, vehicles charge when available and if there is an excess of PV generation. They discharge as and when available and required to provide peak shaving to the building. Vehicle number is calculated.
B4	Building demand, PV generation, vehicles charge when available and if there is an excess of PV generation. Vehicles discharge when available and required within the specified time of use tariff. Vehicle number is specified.
B4.1	Building demand, PV generation, vehicles charge when available and if there is an excess of PV generation. Vehicles discharge when available and required within the specified time of use tariff. Vehicle number is calculated.
M1	Vehicles provide energy to the energy market STOR when available and if called upon. Vehicle number is specified.
M2	Vehicles provide energy to the Capacity Market when available and if called upon. Vehicle number is specified.

SCENARIO B1 – BUILDING PEAK SHAVING WITH KNOWN VEHICLE NUMBERS

With this scenario, the number of vehicles is known and pre-set within the code. The model loads the pre-selected building data required for evaluation before running through the vehicle model a specified number of times. Using the generated EV energy available for discharge, the model then calculates the new building demand profile. An example output from this energy scenario is given in Figure 36.

A. Set vehicle number

Output Format: Set_Vehicle_Number = n

B. Discharge vehicles

See Section 4.3.3 Approach 2.

Output Format: kWh vs. time step.

Table 27 – Vehicle energy available for discharge format

Output Variable Name	Size	Class
Total_Available_Energy_Discharge	48x1	double

B. Calculate new building demand with V2G support

Each time the vehicle model is run, the energy available within the vehicle to discharge is removed from the building demand.

Output Format: Matrix with building demand vs. time step.

Table 28 – New building demand data format

Output Variable Name	Size	Class
New_Building_Demand	48x1	double

Process:

$$Building\ Demand\ with\ V2G = Building\ Demand - \ Energy\ Available\ V2G \tag{29}$$

C. Stop when building demand requirement is satisfied or there are no more vehicles

If the building demand reaches the minimum demand specified before all of the vehicles have been discharged, the simulation stops.

Output Format: Simulation ends.

Process:

$$\begin{gathered} if\ Number\ of\ Vehicles == Set\ Vehicle\ Number \\ OR \\ Building\ Demand \leq Minimum\ Demand \\ END \end{gathered} \tag{30}$$

Where; Set Vehicle Number is the maximum required number of vehicles, building deficit is the energy demand left after EVs have discharged and minimum demand is the lowest value demand is required to drop to.

D. Create graph of results

Output Format: Graph displaying energy demand vs. time step with building demand (with and without V2G support) (Figure 36). By discharging the vehicles evenly over the duration of their stay the model produces a new demand curve similar to the one shown in Figure 36 showing grid energy demand vs time step.

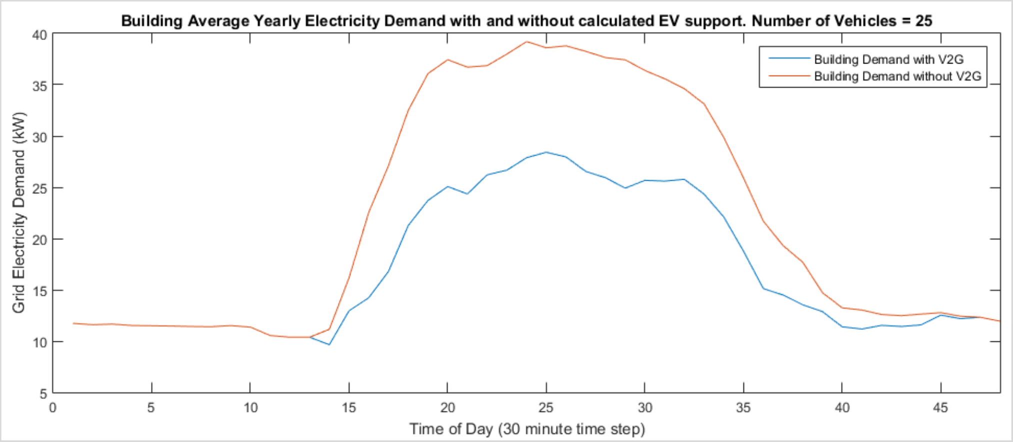


Figure 36 – Example building demand profile for Scenario B1

SCENARIO B1.1 – BUILDING PEAK SHAVING WITH UNKNOWN VEHICLE NUMBERS

Using this sub-model, the software user is able to calculate the number of vehicles required to offset the building demand peak. This is calculated using a loop that adds each vehicle's discharge contribution to the previous building demand curve, stopping when the demand is within a set percentage of the threshold demand value. This is exactly the same as Scenario B1, however a vehicle number is not specified.

A. Add energy available within vehicle to building demand

Output Format: Building demand vs time step.

Table 29 – New building demand data format

Output Variable Name	Size	Class
New_Building_Demand	48x1	double

Process:

See Scenario B1, part B onwards.

B. Stop discharge when threshold value has been reached.

Output Format: End of simulation, see Figure 37.

```
while qq>0;
    VPP_Vehicle_Model_Constant_Sc_12_v1;
    Total_Vehicle_Energy(:,qq) =
Total_Available_Energy_Discharge;
    New_Deficit_Building = Deficit_Building -
Total_Available_Energy_Discharge;
    Deficit_Building = New_Deficit_Building;
    Vehicle_Blanks = sum(Total_Available_Energy_Discharge);

    Number_of_vehicles = qq
    Vehicle_Number = Number_of_vehicles - 1;
    if Vehicle_Blanks == 0;
       Number_of_vehicles = Vehicle_Number & qq == qq-1;
    else qq = qq+1;
    end

       if Number_of_vehicles == Set_Vehicle_Number |
Deficit_Building <= Min_Demand*1.1;
           break;
       end
```

Figure 37 – Code to stop simulation when building deficit has been reached

C. Create Graph of Results

Output Format: Graph displaying energy demand vs. time step with building demand (with and without V2G support) (Figure 38).

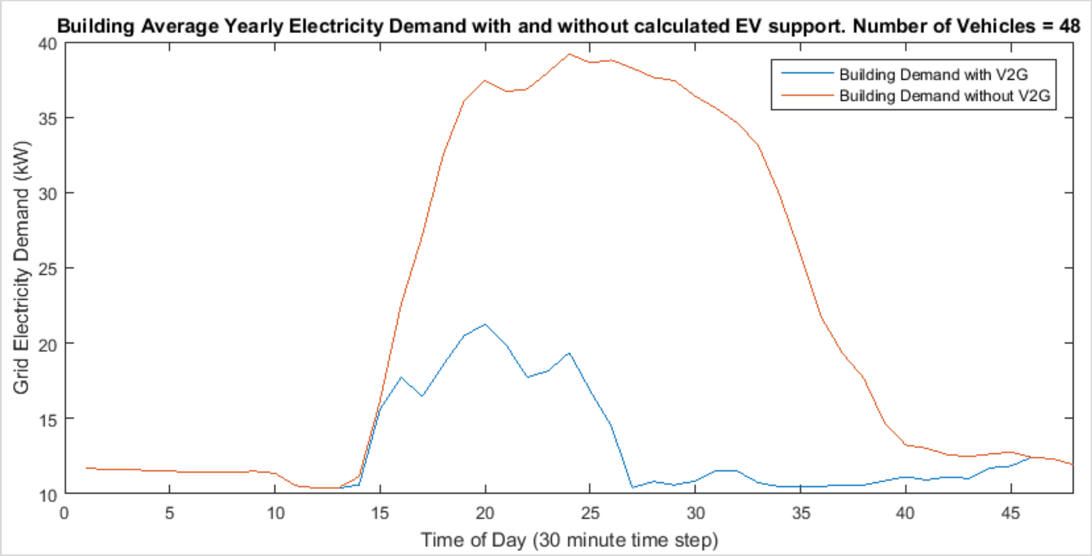


Figure 38 – Example building demand profile for Scenario B1.1

SCENARIO B2 – TOUT DEMAND REDUCTION

This scenario discharges the vehicle based upon a pre-set TOUT. The discharge of the vehicles is therefore triggered to begin at certain times of the day that can be changed depending on the TOUT being employed.

A. Create trigger for vehicle discharging

Output Format: TOUT = [p,q] where p stand for start time and q, end time step.

Table 30 – TOUT data format

Output Variable Name	Size	Class
TOUT	1 x 2	double

B. Create loop to relate start and end of discharge to tariff

Output Format: Replace matrix displaying start and end times and battery levels with tariff information (matrix B). See Figure 39.

```
function [B] = Function_TOUT_v1(B, TOUT)
for oo = 1:size(B,1);
   if TOUT(:,1)> B(oo,1)
       B(oo,1) = TOUT(:,1);
   end
   if TOUT(:,1)< B(:,1)
         B(oo,1) = B(oo,1);
   end
   if TOUT(:,2)> B(oo,3)
       B(oo,3) = B(oo,3);
   end
   if TOUT(:,2)< B(oo,3)
       B(oo,3) = TOUT(:,2);
   end
   if B(oo,1)> B(oo,3)
       B(oo,:) = zeros(1,4);
   end
end
end
```

Figure 39 – Replace start and end times with TOUT values

The process then follows the same procedure as Scenario B1. An example of the expected outputs is shown in Figure 40.

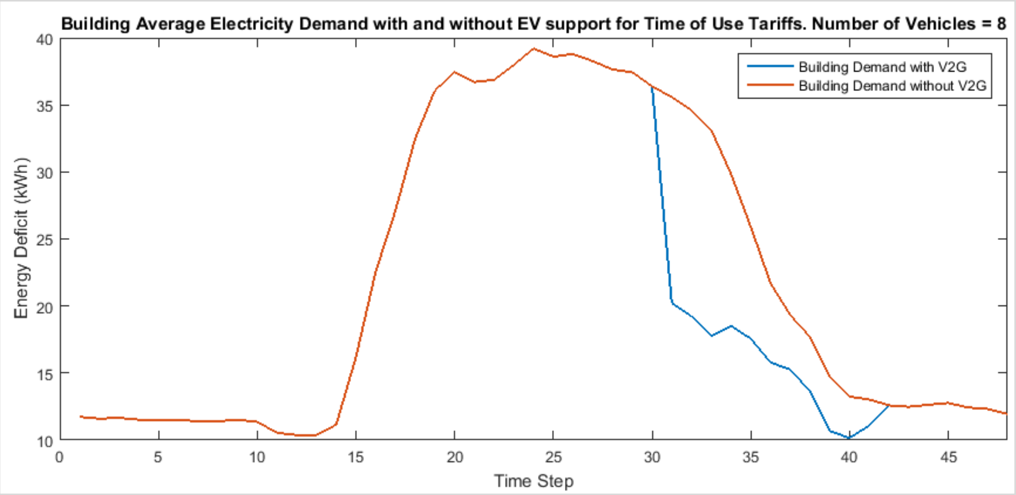


Figure 40 – Scenario B2 example discharging strategy based upon tariff requirements

SCENARIO B3 – PV GENERATION SCENARIO

This scenario follows a very similar pattern to B1 in terms of the method for calculating the number of vehicles required to fulfil demand and the discharge process. However, there is the potential for charging when there is an excess of PV generation, making the operation more complicated.

A. Consume PV energy within the building

Output Format: Building demand vs. time step.

Table 31 – New building demand with PV data format

Output Variable Name	Size	Class
Building_Demand_with_PV	48x1	double

Process:

1. Calculate the energy demand of the building with the addition of PV generation;

$$Final\ Building\ Energy\ Demand = Building\ Energy\ Demand - PV\ Generation \tag{31}$$

B. Remove energy generated from PV and store in the vehicle

The method of calculating the energy storage capacity of the vehicles is already given in the vehicle model. These calculations give an explanation as to how the energy from the building is removed from the demand profile. Figure 41 shows an example profile for charging and discharging of vehicles based upon demand.

Output Format: Building demand vs. time step.

Table 32 – New building demand with PV and V2G data format

Output Variable Name	Size	Class
Building_Demand_with_V2G_PV	48x1	double

Process:

1. Calculate excess PV generation (per time step);

$$Excess\ PV\ Generation = f(Building\ Energy\ Demand, PV\ Generation)t \tag{32}$$

$$Excess\ PV\ Generation = Building\ Energy\ Demand\ - PV\ Generation \tag{33}$$

$$PV\ Storage\ Requirement = \ f(Building\ Demand\ Deficit, Excess\ PV\ Generation)t \tag{34}$$

$$PV\ Storage\ Requirement = \ Building\ Demand\ Deficit -\ Excess\ PV\ Generation \tag{35}$$

2. Add EV charging requirement to building demand profile.

$$New\ Building\ Demand = Building\ Deficit +\ EV\ Charge\ Profile \tag{36}$$

3. Stop when building demand exceeds the charging trigger set.

$$\begin{gathered} If\ f(Building\ Deficit + Storage\ Availability)t \geq 0 \\ f(Charge\ Value) = 0 \end{gathered} \tag{37}$$

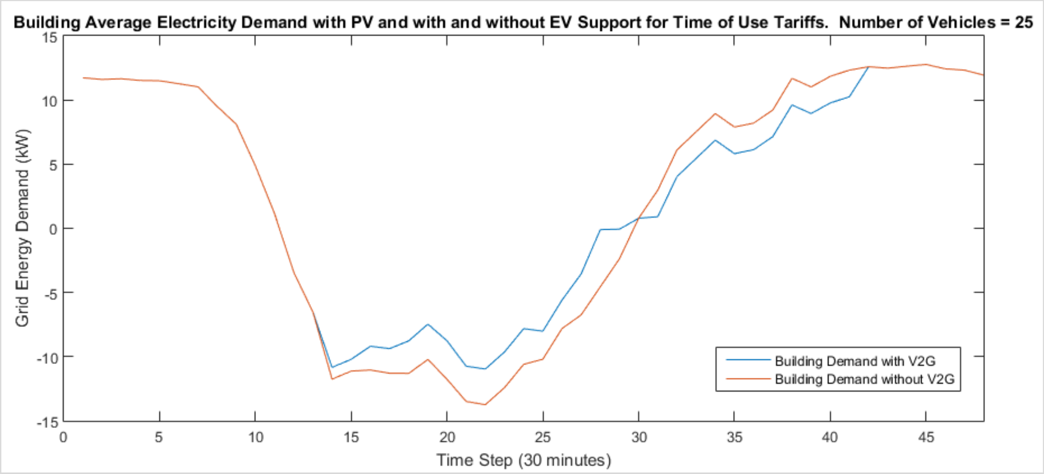


Figure 41 – Example building demand with charging and discharging strategy for Scenario B3

SCENARIO B4 – PV GENERATION AND TOUT DEMAND REDUCTION

This operates in an almost identical way to Scenario B2, the only difference being the addition of the PV generation and therefore a requirement to add charging, as with Scenario B3.

Output Format: Building demand vs. time step.

Table 33 – New building demand with PV and V2G data format

Output Variable Name	Size	Class
Building_Demand_with_V2G_PV	48x1	double

4.6 MARKET MODEL

The market model operates in a similar way to the building model (Scenario B2). However, the discharge strategy is based upon achieving the maximum energy discharge over usually shorter time periods. In Chapter 2, the response requirements were discussed relating to Short Term Operating Reserve (STOR) and the Capacity Market. This information is used within the market model to create restrictions within which the vehicles must operate. Initially a Monte Carlo based simulation identifies the time period the vehicles must discharge. The software user sets the duration of discharge and any other variable parameters relating to the energy scenario. The model will then output the discharge amount from each vehicle to feed into the cost model. The profit received by the vehicle can then be calculated within the cost model. The input/ outputs for the model are given in Figure 42.

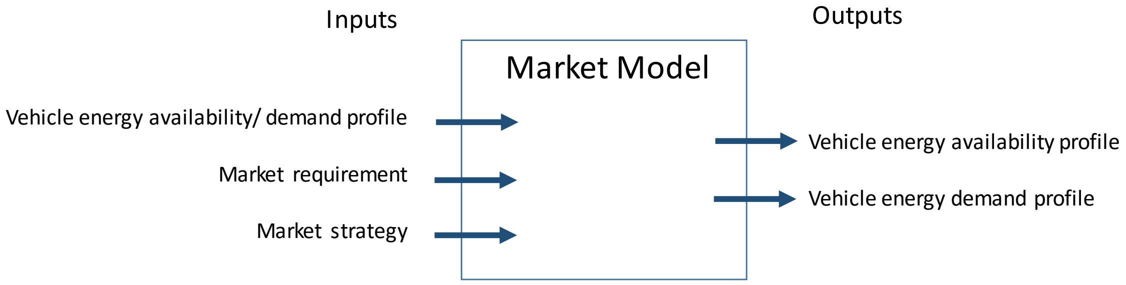


Figure 42 – Market Model Input and Output Requirements

4.6.1 SHORT TERM OPERATING RESERVE CONSUME ENERGY

The first stage of the model relates to the simulation of market triggers for vehicle discharge for STOR. These times are generated from a transition probability matrix, with random numbers generated and compared to the probability matrix. If the output from the comparison is positive, the time step is allocated as time for the vehicles to begin discharging.

A. Set STOR market demand time period

This uses STOR market data to identify the time periods the vehicles might be called upon to provide energy.

Output Format: Discharge window.

Table 34 – Discharge window for STOR model

Output Variable Name	Size	Class
Call_Duration	1x2	double

Process:

1. Set the month of interest (see Figure 43).

```
Market_Type = 1;
% Set the month to subsequently set the window time.
% 1: April
% 2: May-August
% 3: September
% 4: October
% 5: November - January
% 6: February - March
Set_Month = 1;
VPP_Market_Set_Window_v1 % Runs to set the window based on the
month selected
```

Figure 43 – Set energy market model type

2. Set the window of interest based on market and month (see Figure 44).

```
if Set_Month == 1
      Window = [15,28; 39,45];
   elseif Set_Month == 2
       Window = [2,29; 33,37; 40,46];
   elseif Set_Month == 3
      Window = [16,29; 33,44];
   elseif Set_Month == 4
      Window = [16,28; 32,43];
   elseif Set_Month == 5
      Window = [15,28; 33,43];
   elseif Set_Month == 6
      Window = [16,28; 34,43];
   end
```

Figure 44 – Create window for evaluation with market model

B. Discharge vehicles for energy market

Here the market model first simulates a start and end time for the vehicles to discharge within. These times are then run through a ‘for’ loop to replace any arrival and departure times of the vehicles so the discharge period is correct. If the vehicles are unavailable for discharge during the simulated time period, the vehicle is discounted from the system. This operates in the same way as the TOUT to select the discharge period.

Output Format: Energy discharged vs. time step.

Table 35 – Vehicle energy available for discharge into STOR

Output Variable Name	Size	Class
Total_Available_Energy_Discharge	48x1	double

Process:

1. Generate a random number between 1 and 48 with probability density function to assign as a 'call time':

$$P_x(x) = P(X = x) \quad (0 \leq x \leq \ 1)[153] \tag{38}$$

2. If the random number lies within the market window, simulate a response time for the vehicles between 1 and 8.

$$if\ f\big(Window\ Time(Call\ Out)\big) == 1$$

$$Call\ Time = Call\ Out$$

$$else\ Call\ Time = 0$$

3. Calculate the start time for the vehicle discharge as;

$$Start\ Time\ Market = Call\ Time + Response\ Time \tag{39}$$

4. Calculate the end time of the vehicle discharge.

$$End\ Time\ Market = Start\ Time\ Market + 4 \tag{40}$$

5. Run the vehicle model.
6. Set the discharge period within the vehicle model. This is performed using a loop to replace the vehicles existing arrival and departure data with the market requirement (using the same process as for the TOUT start and end time information, as seen in Figure 45).

```
function [B] = Function_STOR_Trigger_v1(B, Call_Duration)
for oo = 1:size(B,1);
       if  Call_Duration(:,1) >= B(oo,1); % If STOR start is larger than start time, replace start time with tariff time
           B(oo,1) = Call_Duration(:,1);
       end
       if Call_Duration(:,1) < B(oo,1); % If STOR start is smaller than start time, keep start time
          B(oo,1) = B(oo,1);
       end
       if Call_Duration(:,2) < B(oo,3); % If STOR end is smaller than end time, replace end time with tariff time
           B(oo,3) = Call_Duration(:,2);
       end
       if Call_Duration(:,2) >= B(oo,3); % If STOR end is larger than end time, keep end time
           B(oo,3) = B(oo,3);
       end
end
end
```

Figure 45 – STOR market start and end time replacement code for vehicle availability

7. Stop when the desired vehicle number has been reached. The result will produce an output as shown in Figure 46 and an indication of the total energy available for discharge from the vehicles.

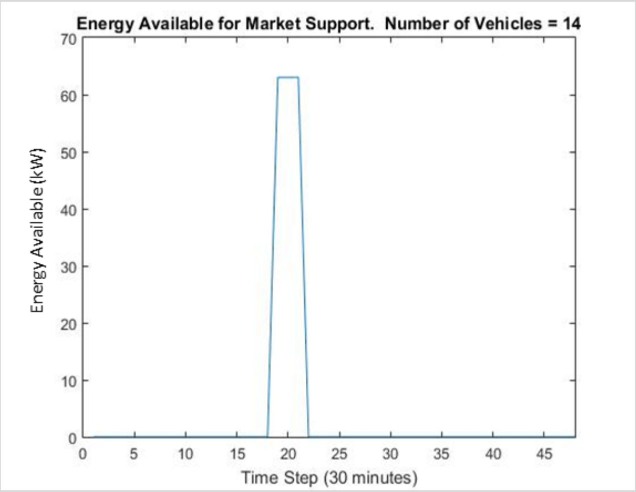


Figure 46 – Example profile of vehicle support for STOR

4.6.2 CAPACITY MARKET CONSUME ENERGY

The operation of the capacity market model is similar to the STOR model; however, the discharge triggers are calculated using real world data probabilities. The data used for analysis in the next chapter is discussed in Section 5.3.5 Capacity Market Data.

A. Set capacity market demand time period

Output Format: Discharge window.

Table 36 – Discharge window for capacity market model

Output Variable Name	Size	Class
Capacity_Duration	1 x 2	double

Process:

1. Set the month of interest.
2. Import probability data (ProbC) and select data based on month of interest.

$$if\ Set\_Month == 1$$

$$ProbCC = January\ data$$

$$elseif\ Set\_Month == N$$

$$ProbCC =' n' data$$

3. Generate 48 random integers between 0 and 100 to assign as ‘x’.
4. Do a comparison of the simulated random numbers with the imported probability, ProbCC. If the simulated random numbers in x are less than the corresponding value in ProbCC, make ‘N’ = 1, else, leave as 0.

$$Comparison\ (N) = x\ \leq ProbCC \tag{41}$$

If N does not contain any ‘1’ values, re-run until sum(N) ≥ 1.

5. At the first occurrence of ‘N’ = 1, take the corresponding matrix number and set as start of discharge.

$$if\ f(N) = 1, Start\ Time\ Capacity = f(N)t \tag{42}$$

6. Set discharge duration. This is a single integer value corresponding to the number of time steps the vehicles must discharge for. For example, Capacity Market Duration = 3 hours which is the equivalent of 6 time steps. This is manually entered by the software user, with the default at 6 time steps.
7. Calculate end time.

$$End\ Time\ Capacity = Start\ Time\ Capacity + Capacity\ Market\ Duration \tag{43}$$

8. Create single matrix with start and end capacity discharge times.

B. Discharge the vehicles for the capacity market

Output Format: Energy discharged vs. time step.

Table 37 – Vehicle energy available for discharge into capacity market

Output Variable Name	Size	Class
Total_Available_Energy_Discharge	48x1	double

Process:

1. Specify the number of vehicles to discharge.

2. Run the vehicle model.

3. Set the discharge period within the vehicle model. This is performed using a loop to replace the vehicles existing arrival and departure data with the market requirement (using the same process as for the TOUT start and end time information, as seen in Figure 45).

```
function [B] = Function_CAPACITY_Trigger_v1(B, Capacity_Duration)
for oo = 1:size(B,1);
       if  Capacity_Duration(:,1) >= B(oo,1) &
Capacity_Duration(:,1) <= B(oo,3) ; % If CAPACITY start is larger
than start time, replace start time with tariff time
           B(oo,1) = Capacity_Duration(:,1);
       end
       if Capacity_Duration(:,1) < B(oo,1); % If CAPACITY start
is smaller than start time, keep start time
          B(oo,1) = B(oo,1);
       end
       if Capacity_Duration(:,2) < B(oo,3) &
Capacity_Duration(:,2) >= B(oo,1); % If CAPACITY end is smaller
than end time, replace end time with tariff time
           B(oo,3) = Capacity_Duration(:,2);
       end
       if Capacity_Duration(:,2) >= B(oo,3); % If CAPACITY end is
larger than end time, keep end time
           B(oo,3) = B(oo,3);
       end
end
end
```

Figure 47 – Capacity market start and end time replacement code for vehicle availability

4. Stop when the specified number of vehicles has been reached.

4.7 COST MODEL

This model calculates the energy savings and costs associated with employing the scenarios evaluated through the software. The output information from the vehicle, building, PV and market models are fed into the cost model to calculate the costs and potential savings for the selected scenario.

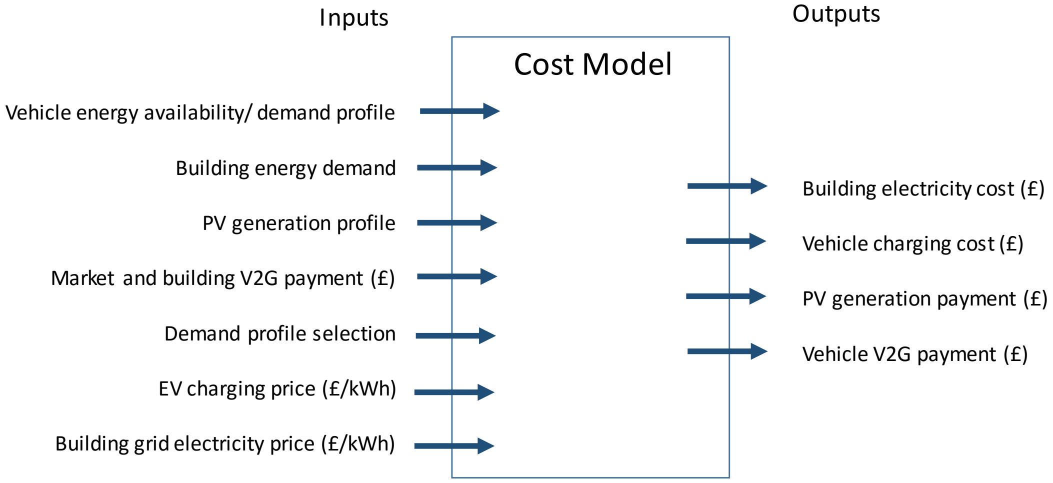


Figure 48 – Cost Model Inputs and Outputs

Seven cost models are considered as follows;

1. Calculate building costs based on set variables.
2. Calculate building costs with TOUT.
3. Calculate building costs with PV.
4. Calculate building costs with PV and TOUT.
5. Calculate market related vehicle and VPP income.
6. Calculate the optimum vehicle V2G tariff and vehicle income.
7. Calculate the optimum V2G infrastructure costs for the building.

These form the basis of the model and are used to feed into the overall output report for the V2GFAE software.

A. Set variables

Output Format: Various single values (see Table 38).

Table 38 – Cost model parameters

Variable Name	Description
Grid_Payment	£/kWh Grid electricity cost
V2G_Tariff	£/kWh Price received by vehicle for electrical discharge
TOUT = [xx,xx]	Tariff parameters for start and end discharge
TOUT_Tariff	£/ kWh TOUT peak electricity cost
TOUT_Off_Tariff	£/kWh TOUT off peak electricity cost
PV_Gen_Tariff	£/kWh PV Generation tariff
PV_Exp_Tariff	£/kWh PV export to grid tariff
EV_Charging_Payment	£/kWh to charge vehicle for V2G energy provided
STOR_Availability_Payment	£/kWh payment for STOR availability
V2G_STOR_Payment	£/kWh utilisation payment for STOR
V2G_Capacity_Payment_Peak	£/kWh for capacity market supply – peak
V2G_Capacity_Payment_OffPeak	£/kWh for capacity market supply – off-peak
Capacity_Capacity_Payment	£/kW for power provision
Years_of_Provision	Number of years of anticipated delivery for Capacity Market
Total_Provision	£ for total MW availability across VPP
VPP_Vehicle_Number	Number of vehicles within the VPP fleet
Capacity_Call_Duration	This specified the duration the vehicles are expected to discharge, measured in 30-minunte time steps
Set_Month	Set the month for evaluation for either STOR or Capacity Market
Installation_Lifetime	Number of years the infrastructure will last
Installation_First	£ - Installation cost of first post
Installation_Sub	£ - Price of installation after first unit
Number_of_days_year	Set number of days the posts will be operational for in one calendar year for V2G services
Charge_Post_Cost	£ - Cost per post
Vehicles_Per_Post	Specify the number of vehicles that can charge per charging post
Battery_Capital_Cost	£ - Capital cost of purchasing the vehicle battery and installing
Battery_Cycles_Drive	Number of cycles for general driving/ vehicle use without V2G
Battery_Cycles_V2G	Number of cycles for the addition of V2G
Battery_Capacity_Stored	kWh total battery capacity

B. Calculate infrastructure costs

Output Format: £.

Output Variable Name: Daily_Install_Costs

Process:

1. Calculate the charge post cost per vehicle.

$$Post\ Cost\ Vehicle = \frac{Charge\ Post\ Cost}{Vehicles\ per\ Post} \tag{44}$$

2. Calculate the installation costs per vehicle.

$$Total\ Installation\ Costs = \frac{(Installation\_First\ + (Number\ of\ Posts\ x\ Installation\_Sub)}{Number\ of\ Posts} \tag{45}$$

$$Installation\ Costs\ per\ Vehicle = \frac{Total\ Installation\ Costs}{Vehicles\ per\ Post}$$

(46)

3. Calculate annual and daily total infrastructure costs.

$$Annual\ Infrastructure\ Costs = \frac{Post\ Cost\ per\ Vehicle + Total\ Installation\ Costs}{Installation\ Life\ Time}$$

(47)

$$Daily\ Infrastructure\ Costs = \frac{Annual\ Infrastructure\ Costs}{Number\ of\ days\ per\ year}$$

(48)

COST MODEL 1 – BUILDING COSTS

This model simply calculates the cost of using the EVs for V2G services. It includes infrastructure costs and various other maintenance and tariff payments. An example of the output summary for all of the cost models is given in Figure 49 that gives a screenshot of the Matlab summary text.

A. Calculate Building Grid Payment

This is the cost of the electricity the building must pay to its supplier for any energy not provided through V2G services.

Output Format: £ vs. time step.

Output Variable Name: Building_Grid_Payment

Table 39 – Building payment to grid without V2G

Output Variable Name	Size	Class
Building_Grid_Payment	48 x 1	Double

Process:

1. Calculate the grid demand if V2G was employed using the outputs from the building model (building demand with V2G support) and multiply by grid tariff.

$$Building\ Grid\ Payment\ = Building\ Demand\ with\ V2G\ x\ Grid\ Tariff$$

(49)

B. Calculate EV added charging cost

This is money paid out to the VPP for V2G services.

Output Format: £ vs. time step.

Table 40 – Building payment to VPP for V2G services

Output Variable Name	Size	Class
Building_Total_V2G_Payment	48 x 1	Double

Process:

1. Calculate cost of charging for V2G deficit. This is the energy consumed during V2G provision that would otherwise not require re-charging.

$$V2G\ Charging\ Cost = V2G\ Energy\ Availabile\ x\ Charging\ Cost \tag{50}$$

2. Calculate V2G demand for building.

$$Building\ V2G\ Demand = Building\ Demand - Building\ Demand\ with\ V2G \tag{51}$$

3. Calculate payment for V2G services.

$$Building\ V2G\ Payment = Building\ V2G\ Demand\ x\ V2G\ Tariff \tag{52}$$

C. Calculate total building costs

This is the cost of the grid and vehicle supplied electricity to the building.

Output Format: £.

Output Variable Name: Building_Daily_Elec_V2G_Costs

Process:

1. Calculate total daily electricity costs.

$$Building\ Electricity\ Costs\ V2G = Building\ Grid\ Payment + Building\ V2G\ Payment \tag{53}$$

2. Calculate total daily costs.

$$Daily\ Building\ Costs\ V2G = Building\ Electricity\ Costs\ V2G + Daily\ V2G\ Install\ Cost \tag{54}$$

D. Calculate total daily savings with V2G

This is the daily saving received by the vehicle through implementation of V2G services.

Output Format: £.

Output Variable Name: Building_Daily_Saving_w_Infra

Process:

1. Calculate electricity costs without V2G. The output format is given in Figure 49 which will be the same for every cost model.

$$Building\ Original\ Costs = Building\ Demand\ x\ Grid\ Tariff \tag{55}$$

2. Calculate daily savings.

$$\begin{aligned} & \mathit{Building\ Daily\ Savings} \\ &= \mathit{Building\ Original\ Costs} - \mathit{Daily\ Building\ Costs\ V2G} \\ &- \mathit{Daily\ Infrastructure\ Costs} \end{aligned} \tag{56}$$

E. Calculate vehicle income

This is the income received by the vehicles on a daily basis for V2G provision.

Output Format: £.

Output Variable Name: Average_V2G_Payment

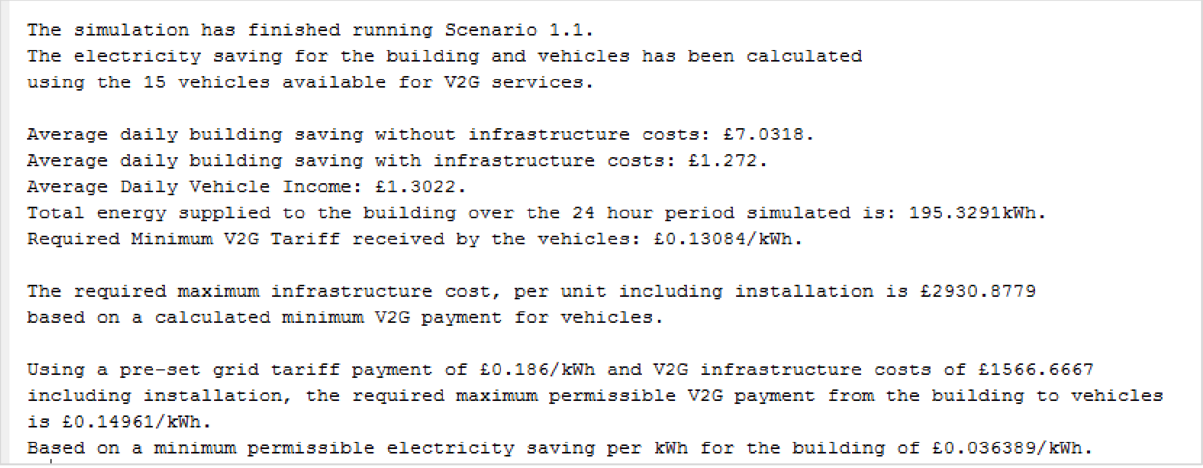
Process:

1. Calculate aggregated V2G income.

$$\mathit{Aggregated\ V2G\ Income} = \mathit{Building\ V2G\ Payment} - \mathit{V2G\ Charging\ Cost} \tag{57}$$

2. Calculate average income per vehicle.

$$\mathit{Average\ V2G\ Income} = \frac{\mathit{Aggregated\ V2G\ Income}}{\mathit{Number\ of\ Vehicles}} \tag{58}$$



```
The simulation has finished running Scenario 1.1.
The electricity saving for the building and vehicles has been calculated
using the 15 vehicles available for V2G services.

Average daily building saving without infrastructure costs: £7.0318.
Average daily building saving with infrastructure costs: £1.272.
Average Daily Vehicle Income: £1.3022.
Total energy supplied to the building over the 24 hour period simulated is: 195.3291kWh.
Required Minimum V2G Tariff received by the vehicles: £0.13084/kWh.

The required maximum infrastructure cost, per unit including installation is £2930.8779
based on a calculated minimum V2G payment for vehicles.

Using a pre-set grid tariff payment of £0.186/kWh and V2G infrastructure costs of £1566.6667
including installation, the required maximum permissible V2G payment from the building to vehicles
is £0.14961/kWh.
Based on a minimum permissible electricity saving per kWh for the building of £0.036389/kWh.
```

Figure 49 – Screenshot of expected output from running Scenario B1

COST MODEL 2 – BUILDING COSTS WITH A TIME OF USE TARIFF

The complexity of this model is related to the identification of a variable grid tariff based upon time of use structures. The grid electricity costs are therefore developed from a single variable to a time relates matrix.

A. Set grid tariff

The cost of electricity from the energy supplier to the building varies throughout the day. Setting the cost as a variable over time is therefore necessary for all future calculations.

Output Format: £/ kWh vs. time step.

Table 41 – TOUT costs

Output Variable Name	Size	Class
TOUT_Off_Tariff_All	48 x 1	Double

Process:

1. Generate grid tariff price based upon time of day. This should be in the form of a 48x1 matrix, using the TOUT matrix specified in Table 38.

$$Grid\ Tariff = f(TOUT\ Off\ Peak, TOUT\ Peak)t \tag{59}$$

B. Calculate Building Grid Payment

Output Format: Matrix £/ time step.

Output Variable Name: Building_Grid_Payment

Process:

$$\begin{gathered} Building\ Grid\ Payment = f(Building\ Demand\ with\ V2G, Grid\ Tariff)\ t \\ Building\ Grid\ Payment = Building\ Demand\ with\ V2G\ x\ Grid\ Tariff \end{gathered} \tag{60}$$

The rest of the cost model is calculated in the same way as Cost Model 1 from part B onwards.

COST MODEL 3 – BUILDING COSTS WITH PV

This model operates in exactly the same way as Cost Model 1, only with the addition of PV generation. PV generation and export payments are therefore included, along with the impact of V2G charging and discharging.

A. Calculate PV income

This calculates the income received by the building by exporting excess PV generation to the grid. There is also a generation payment included.

Output Format: £.

Output Variable Name: Total_Daily_PV_Income

Process:

1. Calculate generation payment.

$$PV\ Generation\ Payment = Total\ Daily\ PV\ Generation\ x\ PV\ Generation\ Tariff \tag{61}$$

2. Calculate PV export amount and the set any negative values to 0.

$$PV\ Export\ Amount = 0 - Building\ Demand\ with\ PV$$

If PV Export Amount < 0, PV Export Amount = 0.

(62)

3. Calculate PV export payment.

$$PV\ Export\ Payment = \ PV\ Export\ Amount\ x\ PV\ Export\ Tariff \tag{63}$$

4. Calculate total PV payment.

$$Daily\ PV\ Payment = \ PV\ Generation\ Payment + \ PV\ Export\ Payment \tag{64}$$

B. Calculate building grid payment with PV only

Output Format: £ vs. time step.

Table 42 – Building payment to grid without V2G

Output Variable Name	Size	Class
Building_Grid_Payment	48 x 1	Double

Process:

1. Calculate payment to the grid without V2G provision.

$$\begin{gathered}Building\ Grid\ Payment\ = \\ (Building\ Demand\ with\ \ PV\ x\ Grid\ Tariff)\end{gathered} \tag{65}$$

2. Where there is an excess of generation and building demand is negative, set payment to zero.

$$if\ Building\ Grid\ Payment\ < 0, Building\ Grid\ Payment(t) = 0 \tag{66}$$

3. Calculate total daily building electricity cost.

$$\begin{gathered}Building\ Original\ Costs\ PV \\ = (Building\ Demand\ with\ PV\ x\ Grid\ Tariff) - Daily\ PV\ Payment\end{gathered} \tag{67}$$

C. Calculate total savings with V2G

Output Format: £.

Output Variable Name: Building_Daily_Saving_w_Infra

Process:

1. Calculate electricity costs without V2G.

2. Calculate daily savings.

$$Building\ Daily\ Savings = Building\ Original\ Costs\ PV - Daily\ Building\ Costs\ V2G \tag{68}$$

D. Use Cost Model 1, part E to calculate vehicle income.

Output Format: Cost (£). Average_V2G_Payment.

<u>COST MODEL 4 – BUILDING COSTS WITH PV AND TIME OF USE TARIFF</u>

This model uses calculations from Cost Model 1, 2 and 3 to calculate the income and savings generated in utilising TOUT discharging in combination with PV generation.

Output Format: £. (Building_Daily_Saving_w_Infra).

<u>COST MODEL 5 – STOR MARKET INCOME</u>

This calculation assumes the vehicles are operating within a virtual power plant (VPP) in order to calculate the availability and delivery payments received by the vehicles. Availability is paid based upon provision of power capability over a set duration, with delivery payments coming from actual energy discharged to the grid.

A. Calculate availability income per day per vehicle

Output Format: £.

Output Variable Name: STOR_Availability_Income

Process:

1. Select income payment variables based on month of interest.

$$if\ Set\_Month == \text{n}$$
$$Availability\ Payment = \cdots ..and\ Provision\ Payment = \cdots.$$
$$and\ so\ on\ \ldots$$

2. Calculate availability income.

$$STOR\ Daily\ Availability\ Income = STOR\ Availability\ Payment\ x\ STOR\ Availability\ Duration\ x\ STOR\ Availability\ Provision \tag{69}$$

3. Calculate daily income from availability per vehicle.

$$Vehicle\ STOR\ Availability\ Payment = \frac{STOR\ Daily\ Availability\ Income}{VPP\ Vehicle\ Number} \tag{70}$$

B. Calculate delivery payment

Output Format: £.

Output Variable Name: Individual_Vehicle_Payment_STOR

Process:

1. Calculate total daily V2G delivery payment.

$$Total\ V2G\ STOR\ payment = Total\ V2G\ Energy\ Discharge\ x\ V2G\ STOR\ Payment \tag{71}$$

2. Calculate vehicle daily V2G delivery payment.

$$Vehicle\ delivery\ payment = \frac{Total\ V2G\ STOR\ payment}{Number\ of\ Vehicles} \tag{72}$$

C. Calculate total daily vehicle payment from STOR

Output Format: £.

Output Variable Name: Total_Daily_STOR_Payment

Process:

$$Total\ Daily\ EV\ Payment = Vehicle\ STOR\ Availability\ Payment + Vehicle\ delivery\ payment \tag{73}$$

COST MODEL 6 – CAPACITY MARKET INCOME

The income generated is based on two payment types. The first is from the capacity provision, paid directly to the VPP and the second is the provision payment for the energy provided by the vehicle to the grid.

A. Calculate the capacity payment to the VPP

Output Format: £.

Output Variable Name: VPP_Daily_Income_Generated

Process:

1. Calculate total income for power provision (kW capacity).

$$Total\ Yearly\ Capacity\ Income = Capacity\ Provision\ Payment\ x\ Total\ Capacity\ Provision\ x\ Years\ of\ Provision \tag{74}$$

2. Calculate total income generated by VPP.

$$Capacity\ Income\ Generated = \ Total\ Yearly\ Capacity\ Income - Total\ Installation\ Costs \tag{75}$$

B. Calculate capacity market provision payment per vehicle

Output Format: £.

Output Variable Name: Average_Daily_V2G_Payment

Process:

1. Calculate EV charging cost (for energy discharged for V2G services).

$$Vehicle\ Charging\ Cost = Total\ V2G\ Energy\ Supplied\ x\ EV\ Charging\ Payment \tag{76}$$

2. Calculate total V2G energy provision.

$$Total\ V2G\ Capacity\ payment = Total\ V2G\ Energy\ Discharge\ x\ V2G\ Capacity\ Payment \tag{77}$$

3. Calculate average daily vehicle income from capacity market.

$$Daily\ V2G\ Payment = \frac{(Total\ V2G\ Capacity\ payment + \ Capacity\ Income\ Generated) - \ Vehicle\ Charging\ Cost}{Number\ of\ Vehicles} \tag{78}$$

4. Calculate payment per kWh of energy supplied for capacity market.

$$Payment\ per\ kWh = \frac{Total\ V2G\ Capacity\ payment}{Total\ V2G\ Energy\ Discharge} \tag{79}$$

<u>COST MODEL 7 – OPTIMUM V2G TARIFF</u>

A cost can be associated to the impact of increased cycling on the lifetime of the battery. This cost model calculates that cost and applies it to a price per kWh of energy supplied. This represents the minimum payment required by the vehicle in order to break even with regards to cost of supplying energy for V2G services. This is calculated based upon the amount of energy discharged, vehicle lifetime and the cost of battery degradation.

A. Calculate cost of V2G cycles on battery

Output Format: £.

Output Variable Name: V2G_Cost

Process:

1. Calculate percentage increase in cycle number due to V2G.

$$Battery\ Increase\ V2G = \frac{Battery\ \ Cycles\ V2G}{Battery\ Cycles\ no\ V2G} \tag{80}$$

2. Calculate cost of V2G cycling.

$$V2G\ Cycling\ Cost = \ Battery\ Increase\ V2G\ x\ Battery\ Capital\ Cost \tag{81}$$

B. Set cost of V2G per kWh energy transfer

Output Format: Cost (£/kWh).

Output Variable Name: V2G_Cost_kWh

Process:

1. Calculate depth of discharge (DoD) for V2G cycling.

$$DoD\ V2G\ Cycling = \frac{Total\ energy\ transferred}{Number\ of\ vehicles} \tag{82}$$

2. Calculate total energy transferred from V2G activities.

$$Total\ V2G\ Discharge = \ DoD\ V2G\ Cycling\ x\ Battery\ Cycles\ V2G \tag{83}$$

3. Calculate cost per kWh for V2G.

$$V2G\ Cost\ per\ kWh = \frac{V2G\ Cycling\ Cost}{Total\ V2G\ Discharge} + EV\ Charging\ Payment \tag{84}$$

COST MODEL 8 – OPTIMUM V2G INFRASTRUCTURE COSTS

This sub-model calculates an optimum infrastructure price based upon a fixed electricity tariff and V2G tariff costs.

A. Calculate maximum infrastructure price

Output Format: £.

Output Variable Name: Total_Equipment_Cost

Process:

Scenarios B1 to B4

1. Calculate difference in V2G payment and grid payment tariffs.

$$Max\ kWh\ Conversion = Grid\ Payment - \ V2G\ Cost\ per\ kWh \tag{85}$$

2. Calculate daily building savings. Infrastructure needs to cost less than this value.

$$Daily\ Savings = \ Max\ kWh\ Conversion\ x\ Total\ V2G\ Energy\ Supplied \tag{86}$$

3. Calculate the maximum daily permissible infrastructure cost.

$$Daily\ Infrastructure\ Costs\ Permissible = \frac{Daily\ Savings}{Number\ of\ Vehicles}\ x\ Vehicles\ per\ Post \tag{87}$$

4. Calculate total infrastructure cost per V2G unit.

$$Maximum\ Infrastructure\ Cost \\ = \ Daily\ Infrastructure\ Costs\ Permissible\ x\ Number\ of\ days\ x\ Installation\ Lifetime \tag{88}$$

Scenarios M1 and M2

1. Calculate total income across entire VPP for year.

$$Total\ VPP\ Income = Vehicle\ Payment\ per\ Day\ x\ Number\ of\ Vehicles \tag{89}$$

2. Calculate maximum costs of individual V2G posts per year.

$$Total\ per\ Year\ Infra\ Costs = \frac{Total\ VPP\ Income}{Number\ of\ Vehicles}\ x\ Vehicles\ per\ Post \tag{90}$$

3. Calculate the total lifetime costs of the infrastructure, including installation.

$$Total\ Infra\ Costs = \ Total\ per\ Year\ Infra\ Costs\ x\ Installation\ Lifetime \tag{91}$$

The cost models developed throughout this section enable a variety of useful outputs to be determined from the V2GFAE software. The benefit of this software however, can only be achieved with the implementation of a graphical user interface (GUI) to enable effective operation and implementation of the code. in making the interface easy and simple to use, the outputs of the software can be fully realised by a non-Matlab user. The next section discusses the development of a simple GUI for the V2GFAE before the output report is developed.

4.8 GRAPHICAL USER INTERFACE

This element of the software provides a clear input screen for the user to prevent them from having to edit the code directly and therefore removes the risk of errors occurring. The GUI needs to have the functionality to enable the user to alter the variables within the model with only a basic understanding of Matlab. The information provided within the GUI should provide them with the knowledge to evaluate a use case of their choice using the scenarios specified within the software. The function of the GUI is to execute the overarching code for the software, which is identified within the systems engineering chapter as the activity diagram for "Create Energy Contract". Initially this process is described before the relation of this to the GUI is demonstrated.

4.8.1 CREATE ENERGY CONTRACT

This provides an overview of the execution code from which the software is implemented. It allows the user to set the energy scenario for evaluation, enter the vehicle, building and market data and run the software.

A. Open software

Output Format: File 'V2GFAE_Software_Open_v1.m' is open and run.

B. Run Energy Scenario

Output Format: USE_CASE = n.m. The following values are accepted: 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 2.1, 2.2 and 2.3. Any numbers outside if this will not return simulation results.

Process:

1. Confirm data is loaded and variables entered as per formats specified in the vehicle, PV, building, market and cost models.

2. Specify energy scenario;

$$Use\ Case = n.m$$

3. Create 'if' statement for scenarios. This allows the software to specify which model and associated cost modes are to be executed.

$$\begin{gathered} if\ Use\ Case = 1.1, Run\ Scenario\ 1.1, Cost\ Model\ 1 \\ elseif\ Use\ Case = 1.2, Run\ Scenario\ 1.2, Cost\ Model\ 2 \\ elseif\ Use\ Case = n.m, Run\ Scenario\ n.m, Cost\ Model\ m \end{gathered} \tag{92}$$

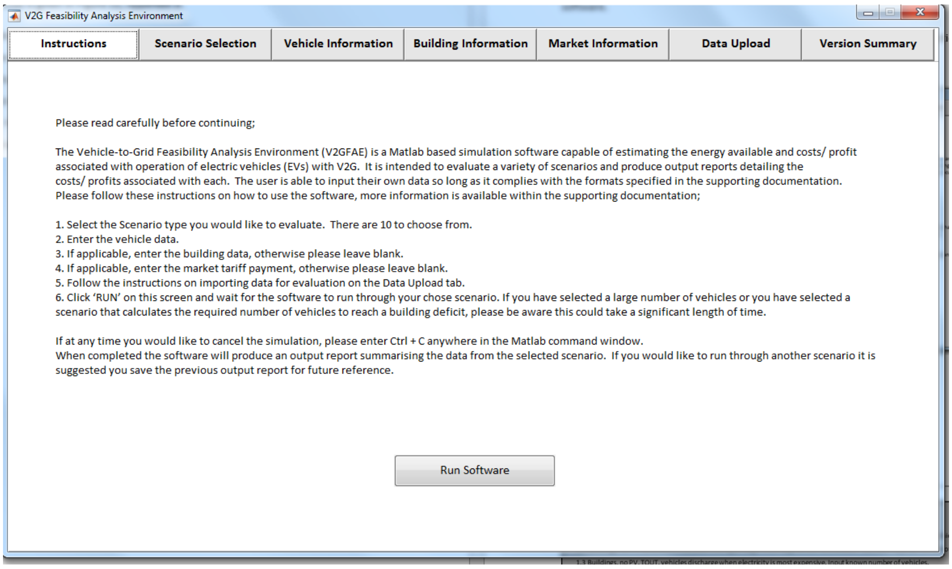
4. Run script.

4.8.2 CREATE GRAPHICAL UNSER INTERFACE

The structure of the GUI is presented with 7 tabs; Information, Scenario Selection, Vehicle, Building Information, Market Information, Data Upload and Version Summary.

The following functionality for each tab screen is required;

1. Instructions (see Figure 50):
    a. Text explaining how to use the software and other functionality including how to cancel the simulation.
    b. 'Run Software' button that executes the V2G FAE software. This can only be executed when all of the other tabs have been evaluated and variables entered.



Please read carefully before continuing;

The Vehicle-to-Grid Feasibility Analysis Environment (V2GFAE) is a Matlab based simulation software capable of estimating the energy available and costs/ profit associated with operation of electric vehicles (EVs) with V2G. It is intended to evaluate a variety of scenarios and produce output reports detailing the costs/ profits associated with each. The user is able to input their own data so long as it complies with the formats specified in the supporting documentation. Please follow these instructions on how to use the software, more information is available within the supporting documentation;

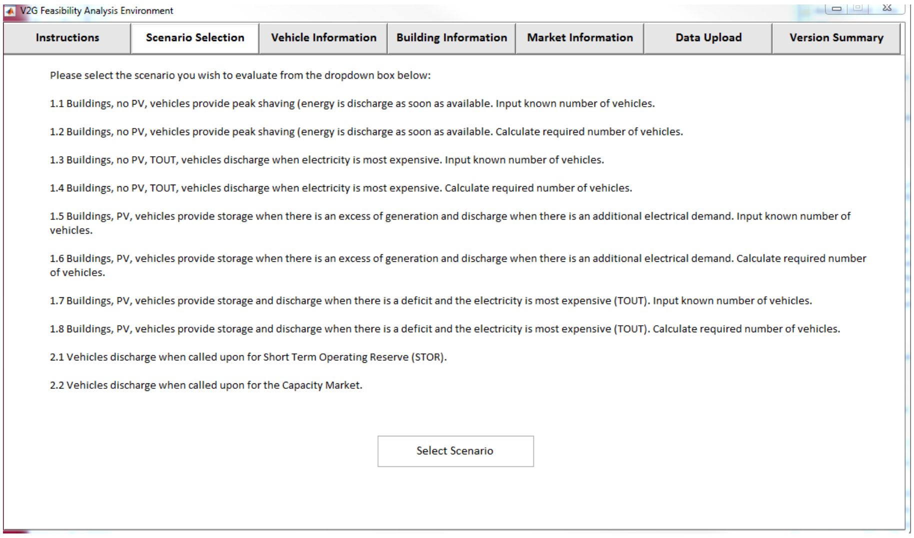
1. Select the Scenario type you would like to evaluate. There are 10 to choose from.
2. Enter the vehicle data.
3. If applicable, enter the building data, otherwise please leave blank.
4. If applicable, enter the market tariff payment, otherwise please leave blank.
5. Follow the instructions on importing data for evaluation on the Data Upload tab.
6. Click 'RUN' on this screen and wait for the software to run through your chose scenario. If you have selected a large number of vehicles or you have selected a scenario that calculates the required number of vehicles to reach a building deficit, please be aware this could take a significant length of time.

If at any time you would like to cancel the simulation, please enter Ctrl + C anywhere in the Matlab command window.
When completed the software will produce an output report summarising the data from the selected scenario. If you would like to run through another scenario it is suggested you save the previous output report for future reference.

Figure 50 – Introduction page for V2GFAE

In pressing the 'Run Software' button the GUI executes a command to run the script containing the code to run through the V2GFAE software. This push button command will only execute if all the other data entry tabs have been completed, otherwise an error message will appear.

2. Scenario Selection (see Figure 51):
    a. Information detailing the various scenarios the software can run through.
    b. Dropdown box with each scenario number in for selection.



Please select the scenario you wish to evaluate from the dropdown box below:

1.1 Buildings, no PV, vehicles provide peak shaving (energy is discharge as soon as available. Input known number of vehicles.

1.2 Buildings, no PV, vehicles provide peak shaving (energy is discharge as soon as available. Calculate required number of vehicles.

1.3 Buildings, no PV, TOUT, vehicles discharge when electricity is most expensive. Input known number of vehicles.

1.4 Buildings, no PV, TOUT, vehicles discharge when electricity is most expensive. Calculate required number of vehicles.

1.5 Buildings, PV, vehicles provide storage when there is an excess of generation and discharge when there is an additional electrical demand. Input known number of vehicles.

1.6 Buildings, PV, vehicles provide storage when there is an excess of generation and discharge when there is an additional electrical demand. Calculate required number of vehicles.

1.7 Buildings, PV, vehicles provide storage and discharge when there is a deficit and the electricity is most expensive (TOUT). Input known number of vehicles.

1.8 Buildings, PV, vehicles provide storage and discharge when there is a deficit and the electricity is most expensive (TOUT). Calculate required number of vehicles.

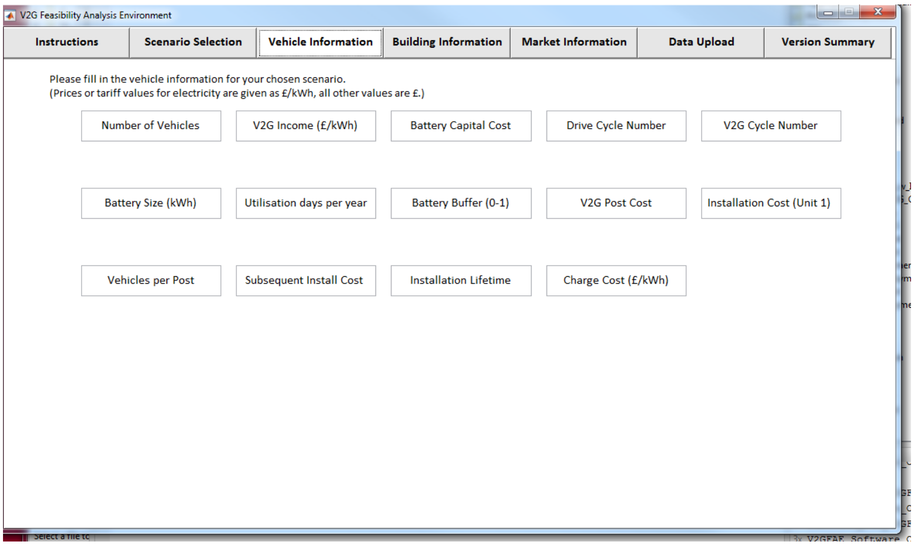
2.1 Vehicles discharge when called upon for Short Term Operating Reserve (STOR).

2.2 Vehicles discharge when called upon for the Capacity Market.

Figure 51 – Scenario selection page for V2GFAE

In selecting a scenario from the dropdown list the GUI generates a variable to be run through the V2GFAE software that determines the scenario to be evaluated. Vehicle Information (see Figure 52):

a. Edit textboxes to enter information on all variables related to vehicles under evaluation. These are; number of vehicles, V2G tariff price, vehicle list price, vehicle grant, yearly insurance cost, yearly maintenance fee, yearly tax cost, yearly management fee, battery service cost, battery capital cost and ownership period.

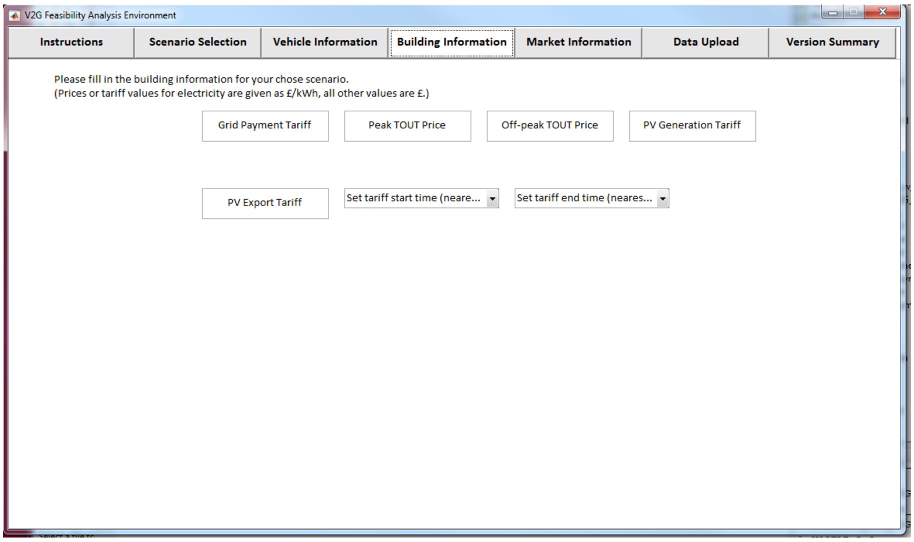


Please fill in the vehicle information for your chosen scenario.
(Prices or tariff values for electricity are given as £/kWh, all other values are £.)

Figure 52 – Vehicle data entry page for V2GFAE

All the data entered into the vehicle, building and market information sections are used to create variables within the workspace that are used throughout the software to define the parameters of the scenario.

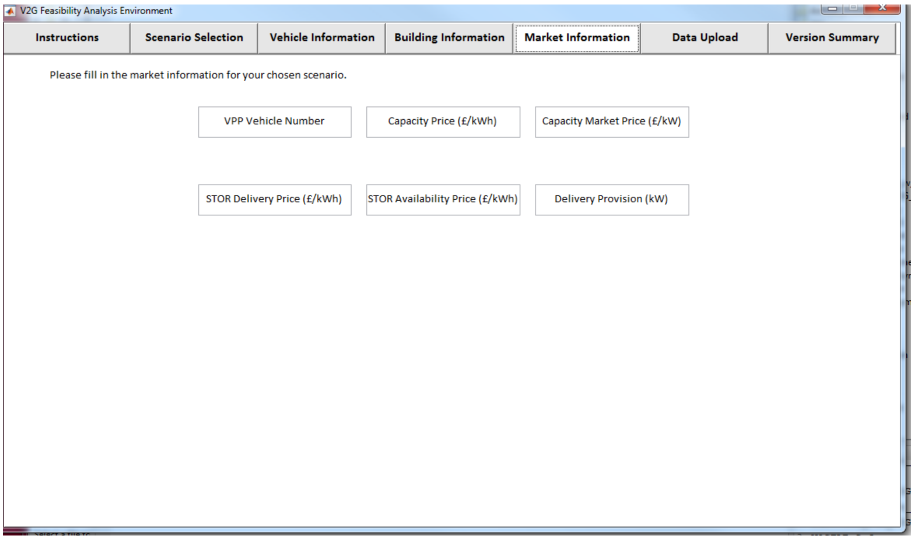
1. Building Information (see Figure 53):
    a. Edit textboxes to enter information on all variables related to the buildings under evaluation. These are: grid payment tariff, time of use tariff, charge post cost, number of vehicles per post, installation cost, installation lifetime, time of use tariff start time and time of use tariff end time (to nearest 30 minutes).



Please fill in the building information for your chose scenario.
(Prices or tariff values for electricity are given as £/kWh, all other values are £.)

Figure 53 – Building data entry page for V2GFAE

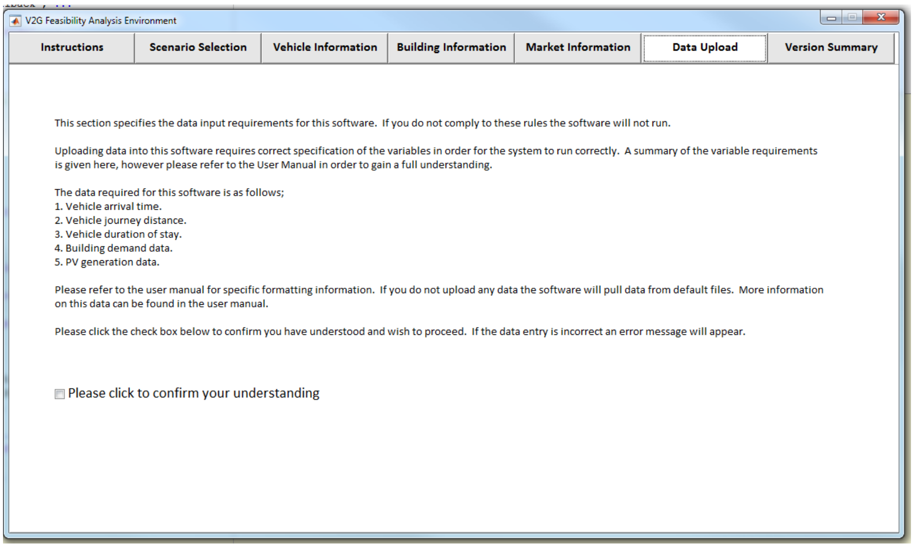
2. Market Information (see Figure 54):
    a. Editable textbox to enter the payment tariff received by the vehicle from the energy market.



Please fill in the market information for your chosen scenario.

Figure 54 – Market data entry page for V2GFAE

3. Data Upload (see Figure 55):
    a. Information relating to how the data should be uploaded for the software and information relating to where additional formatting and requirements can be found.
    b. Checkbox to confirm the user has understood the data requirements of the software.



This section specifies the data input requirements for this software. If you do not comply to these rules the software will not run.

Uploading data into this software requires correct specification of the variables in order for the system to run correctly. A summary of the variable requirements is given here, however please refer to the User Manual in order to gain a full understanding.

The data required for this software is as follows;
1. Vehicle arrival time.
2. Vehicle journey distance.
3. Vehicle duration of stay.
4. Building demand data.
5. PV generation data.

Please refer to the user manual for specific formatting information. If you do not upload any data the software will pull data from default files. More information on this data can be found in the user manual.

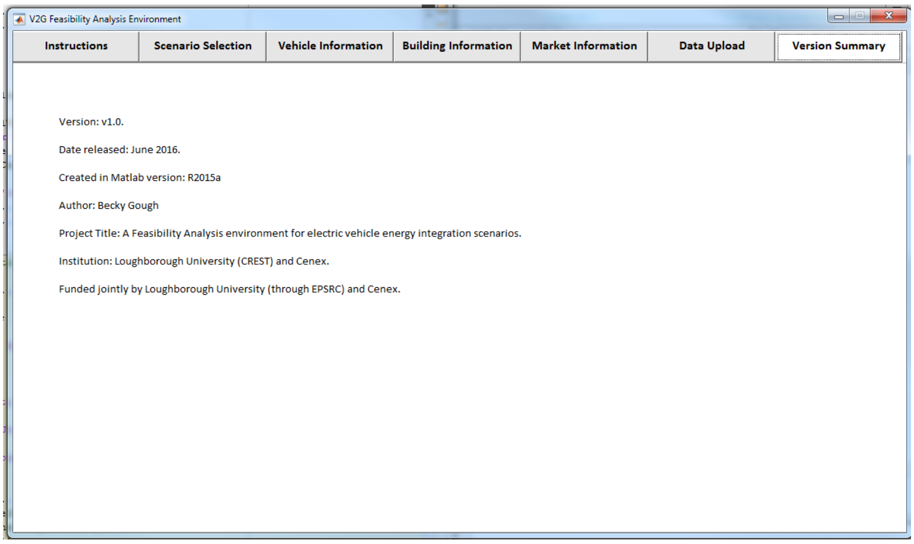
Please click the check box below to confirm you have understood and wish to proceed. If the data entry is incorrect an error message will appear.

☐ Please click to confirm your understanding

Figure 55 – Data upload data entry information page for V2GFAE

The information given in the 'Data Upload' section does not allow the software user to input new data. Instead it offers information on what the data requirements are and directs the user to the software manual. Using this manual, the user is able to import data to the required format for evaluation. The user is not able to continue with the simulation until the checkbox is selected to confirm the users understanding.

4. Software Version Summary (see Figure 56):
    a. Information relating to the software version, release date and size.



Version: v1.0.

Date released: June 2016.

Created in Matlab version: R2015a

Author: Becky Gough

Project Title: A Feasibility Analysis environment for electric vehicle energy integration scenarios.

Institution: Loughborough University (CREST) and Cenex.

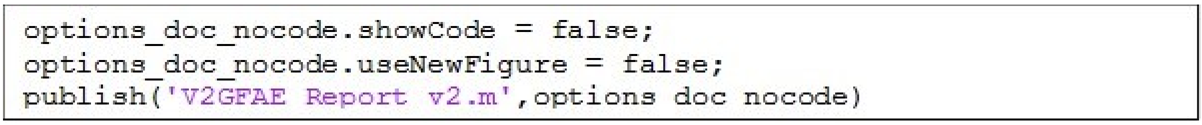
Funded jointly by Loughborough University (through EPSRC) and Cenex.

Figure 56 – Version Summary for V2GFAE

4.9 OUTPUT REPORT

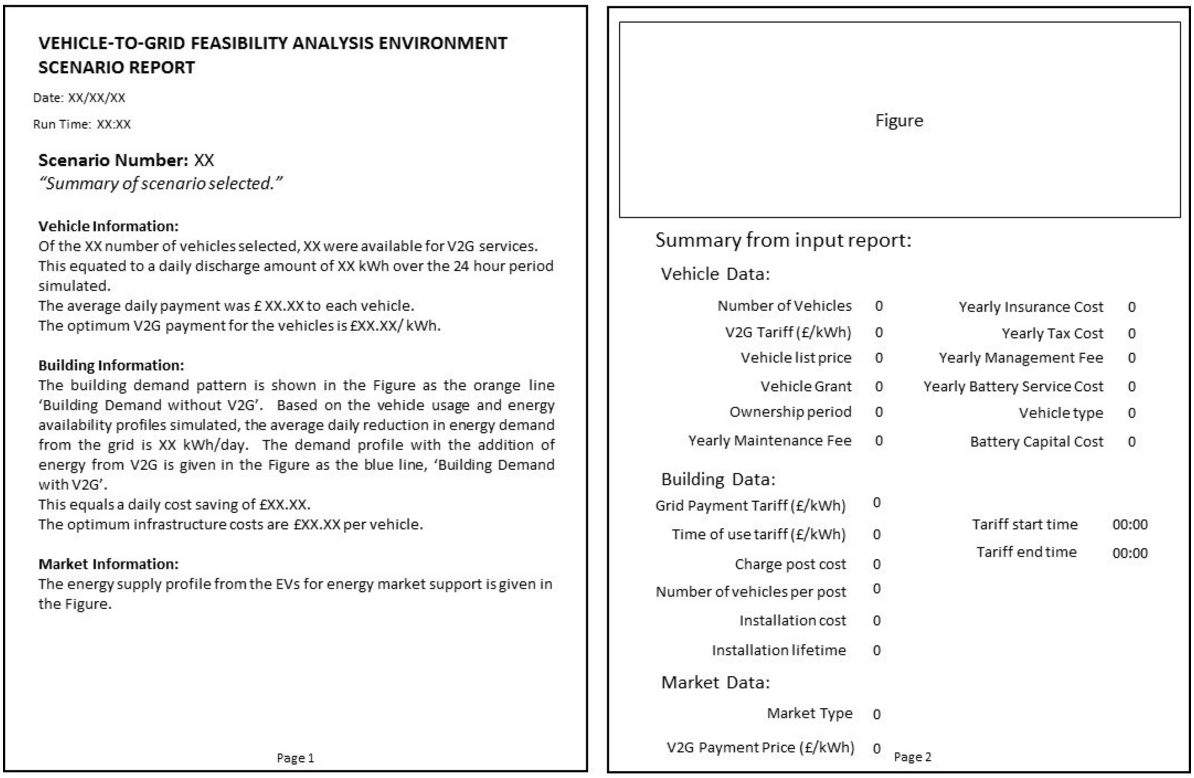
The output report provides a summary of the information produced from the analysis of the selected scenario. The software user has the ability to save the output report and re-run the software to select a different set of outcomes to enable the user to compare outputs from the analysis. The layout is given in Figure 58, depicting a summary of the economic result from running the input data through the selected scenario. Other key features include graphical display of the vehicle energy availability profiles and building grid demand profiles pre and post EV/ V2G intervention.

The 'publish' function is used to create the output report. This calls upon a script file that contains text relating to the 'fprintf 'function. This produces text usually displayed in the Matlab workspace however for the purposes of the report it is printed into a html format instead. Figure 57 displays the 'publish' function used to call upon the report text script. An example of the report is given in Appendix B.



```
options_doc_nocode.showCode = false;
options_doc_nocode.useNewFigure = false;
publish('V2GFAE Report v2.m',options doc nocode)
```

Figure 57 – Code for publishing V2GFAE output report



VEHICLE-TO-GRID FEASIBILITY ANALYSIS ENVIRONMENT SCENARIO REPORT

Date: XX/XX/XX

Run Time: XX:XX

Scenario Number: XX

"Summary of scenario selected."

Vehicle Information:

Of the XX number of vehicles selected, XX were available for V2G services. This equated to a daily discharge amount of XX kWh over the 24 hour period simulated.
The average daily payment was £ XX.XX to each vehicle.
The optimum V2G payment for the vehicles is £XX.XX/ kWh.

Building Information:

The building demand pattern is shown in the Figure as the orange line 'Building Demand without V2G'. Based on the vehicle usage and energy availability profiles simulated, the average daily reduction in energy demand from the grid is XX kWh/day. The demand profile with the addition of energy from V2G is given in the Figure as the blue line, 'Building Demand with V2G'.
This equals a daily cost saving of £XX.XX.
The optimum infrastructure costs are £XX.XX per vehicle.

Market Information:

The energy supply profile from the EVs for energy market support is given in the Figure.

Page 1

Figure

Summary from input report:

Vehicle Data:

Number of Vehicles	0	Yearly Insurance Cost	0
V2G Tariff (£/kWh)	0	Yearly Tax Cost	0
Vehicle list price	0	Yearly Management Fee	0
Vehicle Grant	0	Yearly Battery Service Cost	0
Ownership period	0	Vehicle type	0
Yearly Maintenance Fee	0	Battery Capital Cost	0

Building Data:

Grid Payment Tariff (£/kWh)	0		
Time of use tariff (£/kWh)	0	Tariff start time	00:00
Charge post cost	0	Tariff end time	00:00
Number of vehicles per post	0		
Installation cost	0		
Installation lifetime	0		

Market Data:

Market Type	0
V2G Payment Price (£/kWh)	0

Page 2

Figure 58 – Draft layout for output report

4.10 CHAPTER SUMMARY

The V2GFAE is a multi-level simulation tool, created to evaluate the suitability of EVs to act as portable battery storage devices. Following the MDA approach to software development created in Chapter 3, the software has been developed around activity and class diagrams. Each activity diagram description has formed the basis of the system architecture, with the connections and links between each activity developed as a result of the class diagram created in Chapter 3. This clearly demonstrates the robust nature of the system architecture design process, with an iterative process being followed that allowed for rigorous system build.

The bottom up stochastic modelling approach of the software allows for enhanced flexibility in evaluating multiple case studies. Using data as the base for the simulation and then building on it through Monte Carlo based simulation, the software is able to perform multiple evaluations at a time. The vehicle model forms the basis for the simulation, with the subsequent building, PV and market models simulating vehicle support opportunities based on outputs from the vehicle model. The outputs of these simulations are fed into the cost model, which establishes the economics of the energy scenario evaluated, allowing the software user to make an informed decision as to the suitability of EVs with V2G for the energy scenario evaluated.

Looking at the outputs from the V2GFAE and the requirements definition given in Chapter Three, a first pass view evaluates the requirements as having been fulfilled. However, the functionality and usefulness of the data output from the software is yet to be fully evaluated and all of the functionality explored. The following chapter uses the V2GFAE software to evaluate a case study to understand how users might maximise its outputs, in addition to performing system build validation. Chapter Six provides verification and validation of the software to confirm its performance against the initial system requirements.

CHAPTER FIVE

CASE STUDY ANALYSIS

5.1 INTRODUCTION

This chapter performs two purposes; to test the software developed in Chapter 4 for software validation purposes and to evaluate a case study using the software. This process is performed following the systems engineering 'Vee' given in Figure 59, "Testing to Specification" and Chapter 3. The analysis in this chapter will use Manchester Science Park (MSP) as the case study to establish the economic viability of vehicle-to-grid (V2G) to answer the following questions:

1. What impact does the vehicle usage profile have on their ability to provide battery storage provision, both locally and for energy market trading? Two usage profiles are of primary interest; commuting and pool vehicles.
2. What impact does the payment tariff for EV support have on the economic suitability of EVs to provide battery storage provision?
3. What is the overall suitability of electric vehicles as battery storage devices? Is one energy scenario support option more suitable than another depending upon electricity provision requirements?
4. What is the calculated environmental impact or benefit of V2G services to the UK?

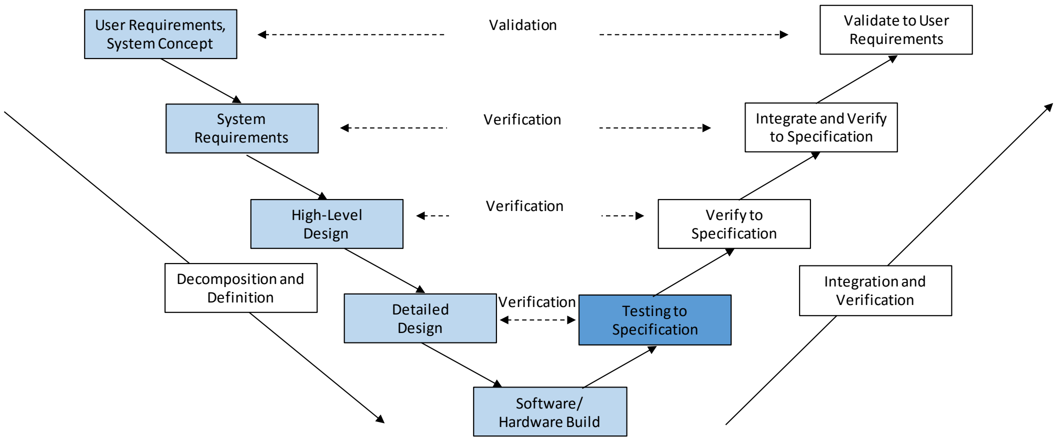


Figure 59 – Testing to Specification Phase of Systems Engineering 'Vee' Process

Initially the case study and data is described before a preliminary case study to evaluate the general suitability of V2G at the Science Park. Using the scenarios and cost models created within the Vehicle-to-Grid Feasibility Analysis Environment (V2GFAE), the significance of the vehicle usage profiles on the suitability of the vehicles for V2G services is evaluated, along with the impact of electricity tariffs and infrastructure pricing.

5.2 CASE STUDY DESCRIPTION

MSP is located in south Manchester and comprises six mixed use commercial buildings, the use types of which are given in Table 43. Due to the mixed use of the buildings including data centres, labs and general office space there is a large variation in the floor area of the buildings and electrical consumption. There are a number of external businesses that rent unit space from MSP, as well as MSP employees who work on the site and operate a number of pool vehicles.

Table 43 – Manchester Science Park building energy consumption

Building	**Use Type**	**Floor Area (m^2)**	**Total Yearly Consumption (kWh/m^2)**
Enterprise	Office space and small lab space	2268.88	170.88
Greenheys	Office space and small lab space	2723.45	159.36
Kilburn	Office space with data centre	3247.61	66.72
Rutherford	Office space and small lab space	2116.24	54.52
Skelton	Medical research facility	3997.52	255.07
Williams	Office space with data centre	3182.21	35.23

The electricity consumed by MSP is charged based on triads which are explained in Chapter 2, Section 2.2.4 Aggregation Services. These charges are a variable monthly fee based on 85% of the monthly maximum demand or a fixed monthly fee based on a 12th of the forecasted triad demand [102]. More information on how this is calculated is given in Section 5.4.2.3. If the maximum demand readings for each triad period can be reduced, the cost of the triad could be reduced, hence reducing the yearly electricity cost for MSP by up to ~£22,000. The company have proposed to increase the number of pool vehicles operating from the site as well as incentivise existing tenants to buy into a V2G scheme in exchange for a reduced rental value. They would therefore like to discover if V2G is a possibility at their commercial premises, either through paying commuting tenants for their energy, or through utilisation of their own pool vehicle fleet. The analysis in this chapter will therefore explore the suitability of the vehicles located at the Science Park in providing economic benefit through V2G services to MSP. This involves exploring the impact of reducing the triad charges through peak shaving and other electricity charge types such as time of use tariffs (TOUT) and flat rate charging for comparison purposes.

5.3 DATA DESCRIPTION

There are five data sets used for analysis in this chapter; vehicle telemetry data, building data, simulated PV data, simulated Short Term Operating Reserve (STOR) and wholesale market data. This section briefly describes how the data were validated before being entered into the V2GFAE for scenario analysis.

5.3.1 BUILDING DEMAND DATA

MSP consists of six buildings and 736 parking spaces. The data was collected from the 30th June 2014 to the 30th June 2015 in half-hourly demand periods for each building. The weekends were excluded as commuting patterns will only occur Monday to Friday, leaving 266 days and an average of 22 days per month. The data was initially evaluated to establish the maximum, minimum and average values for the half hourly energy demand to identify any extreme outliers. Table 44 shows the average yearly standard deviation, maximum, minimum and average values for each of the six buildings on the science park. Variation between data points for all buildings is within +/- 4 standard deviations with the exception of the Skelton Building. This is due to the use type being a medical facility, meaning at certain times the demand is likely to have large variations depending upon the research and testing being performed. To demonstrate the variation in demand over the course of a year, the average, maximum and minimum demand per half hour of the day is given in Figure 60 (detailed by the green data points). This is also compared to demand with PV generation discussed in the next section.

Table 44 – Manchester Science Park Demand per Half-Hour

	SD	Max (kWh)	Min (kWh)	Ave (kWh)
Enterprise	2.75	27.40	16.94	23.15
Greenheys	3.46	33.65	20.49	27.22
Kilburn	2.31	18.00	9.27	12.48
Rutherford	0.62	8.15	5.70	6.95
Skelton	6.22	86.22	60.99	75.36
Williams	0.42	7.22	5.64	6.37
Average Science Park	**2.63**	**30.11**	**19.84**	**25.25**

5.3.2 PV GENERATION DATA

PV data has been calculated using a PVSyst model to estimate the average hourly generation for each building based upon the roof area and shading (supplied by M. Jhagra [155]). PVSyst is a software programme designed to help planners evaluate the PV generation potential of rooftops and other areas based on geographic location, shading, sunlight and so on. In order to convert the data into a usable format for comparison with the half hourly building demand, the data was averaged across each half hour and smoothed in MATLAB using the following process to produce an average half-hourly value:

1. Average generation from each hour to ½ hour time steps;

$$\frac{1}{2}Hourly\ Generation = \frac{Hourly\ Generation}{2}$$

(93)

2. Smooth data using a moving average filter;

$$y_s(i) = \frac{1}{2N+1}(y(i + N0 + y(i + N - 1) + \cdots + y(i - N))$$

(94) [156]

Where; $y_s(i)$ is the smoothed value for the i^{th} data point, N is the number of neighboring data points on either side of $y_s(i)$ and 2N+1 is the span.

Applying these generation profiles to the building electricity demand of MSP results in the profiles displayed in Figure 60, where the average, maximum and minimum building demand per half-hour of the day is displayed (blue data points) in comparison to the original building demand. From these profiles three buildings generate an excess of PV energy at certain points in the year (Enterprise, Rutherford and Williams buildings). As the Skelton building has the greatest demand, PV has a relatively small proportional effect in reducing electricity demand.

The Enterprise Building has a large roof area suitable for PV and therefore modelling has shown it could produce an excess of electricity during the summer months, as could Rutherford and Williams Buildings, but to a lesser extent. The sharp spikes demonstrated for the Kilburn Building due to the data centre are marginally reduced during summer months, however the Williams Building has a much more reduced demand profile from PV support. With the relatively poor roof area for PV, the Greenheys Building would experience the lowest impact from the PV generation modelling due to its relatively large electricity demand. When aggregating up the demand of all six buildings to consider the Science Park as a whole, the variation in demand with and without PV is shown in Figure 61. This indicates that whilst the simulated PV generation does reduce demand down to below 50kWh during the middle of the day, demand is never low enough to warrant uptake of a PV charging related scenario as it does not reach a 0kWh threshold where electricity is exported to the grid.

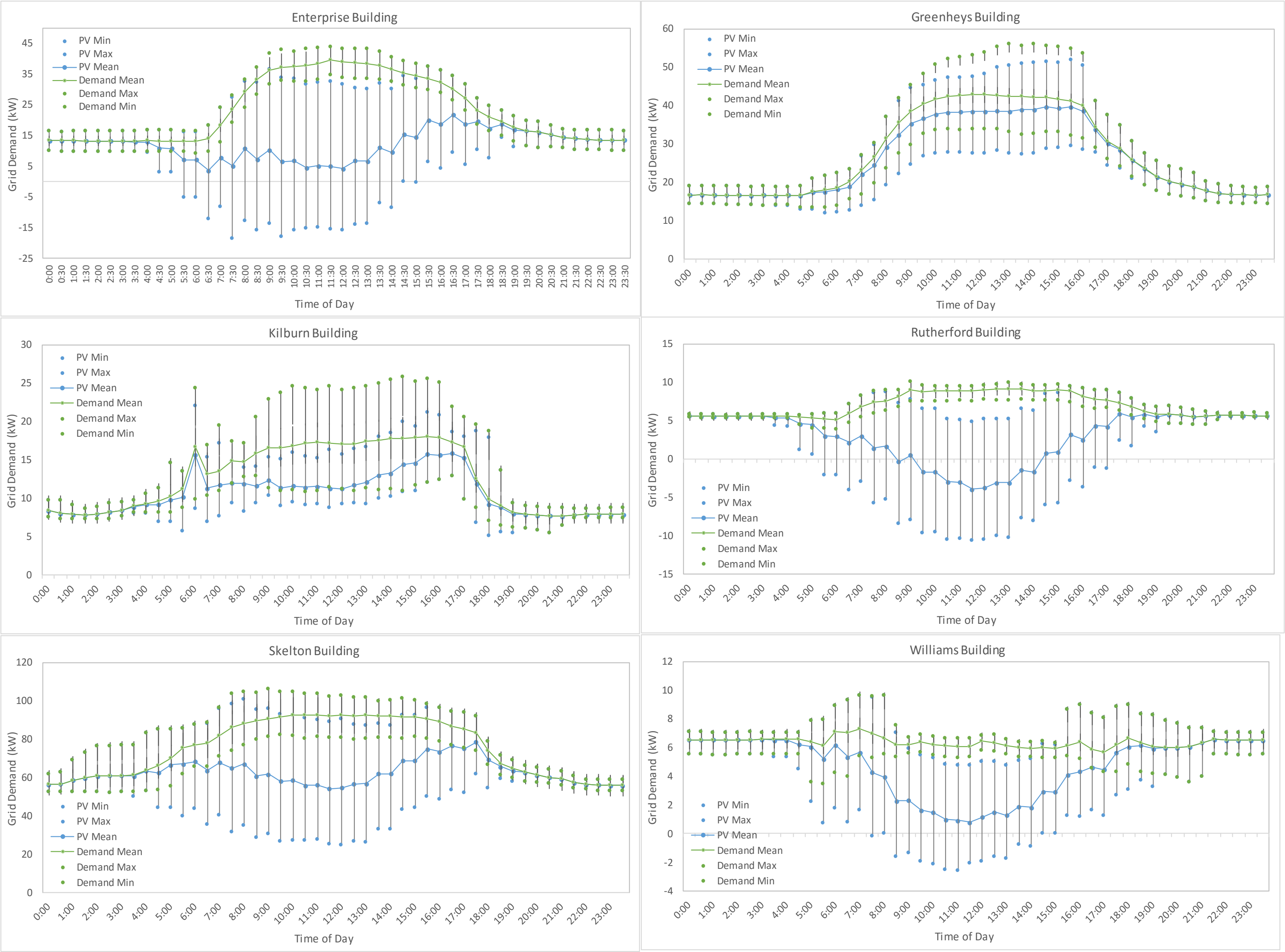


Figure 60 – MSP building demand profiles with and without PV generation

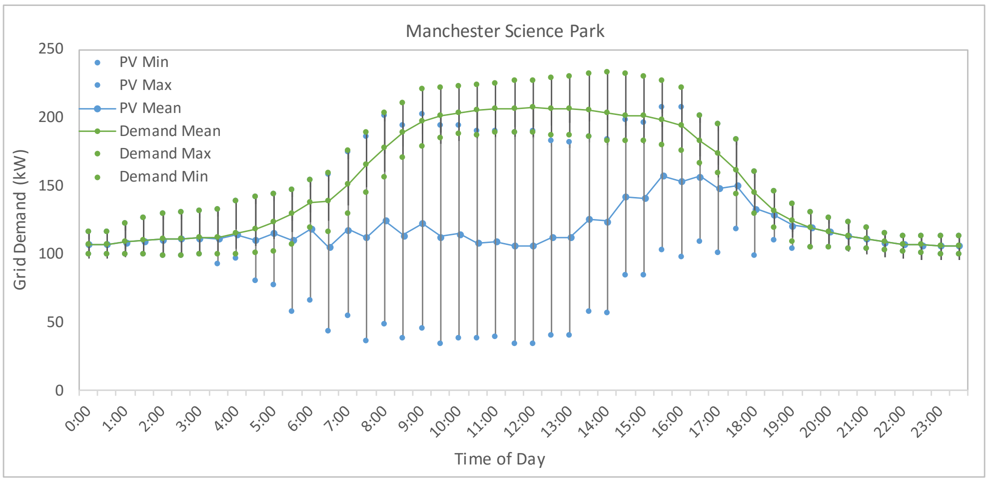


Figure 61 – Aggregated MSP demand with and without PV generation

The Enterprise Building has a relatively low electricity demand profile when compared to the PV generation opportunities for the building. This means that during certain months of the year, excess electricity could be available and exported to the grid or consumed by EVs for charging and then discharged back into the building later on in the day. Figure 62 demonstrates the impact of using 25 vehicles for EV discharging when demand exceeds generation and charging during periods of excessive PV generation. July has the greatest excess of PV generation for any month for the Enterprise Building simulated. For the analysis conducted in this study two building demand profiles are used; aggregated demand of the Science Park and data from an average July day for the Enterprise Building. This demonstrates two different demand types for comparison purposes; one high and one low with excess PV generation during the analysis period.

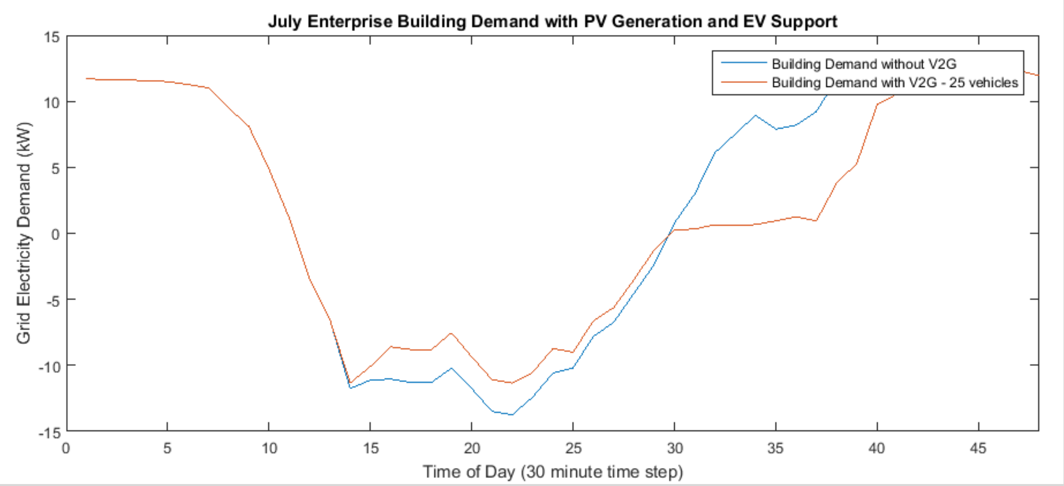


Figure 62 – Enterprise Building July building demand with PV generation and V2G intervention with 25 vehicles

5.3.3 VEHICLE TELEMETRY DATA

The data sets relating to vehicle telemetry are separated into commuter and pool vehicles. Commuter vehicles are those that travel to and from work every weekday on a commuting basis and can be charged at both home and work. Pool vehicles are based entirely at the work place, as is all of the charging and they are usually driven during the day. This data set is extremely large, from a field trial run in the UK from January 2011 to June 2012, where telemetry was installed on 349 electric vehicles. The information collected from the vehicles is summarised in Table 45.

Table 45 – Vehicle telemetry data fields

Charging Energy Dataset	
Variable Field Name	**Unit**
Charge ID	Number
Consortium ID	Text
Vehicle ID	Text
Start SoC	%
End SoC	%
Energy Consumed	kWh
Charge Location	Text
Start Date	Date
Start Time	Time
End Date	Date
End Time	Time
User type	Text
Usage type	Text
Infrastructure Location	Text

Journey Energy Dataset	
Variable Field Name	**Unit**
Consortium ID	Text
Vehicle ID	Text
Distance Travelled	Km
Start SoC	%
End SoC	%
Used SoC	%
Energy Used	kWh
Start Date	Date
Start Time	Time
End Date	Date
End Time	Time
User Type	Text
Usage Type	Text
Infrastructure Location	Text

Due to the novelty of the telemetry technology installed in the vehicles, validation of the data is imperative to ensure results from the V2GFAE are accurate. Data of key interest is the start and end times of journeys and charging events, with any journeys with the same start and end time requiring elimination if an energy consumption value exists. Eight journeys had end times before their start times from the whole dataset and were removed as erroneous data.

COMMUTER VEHICLES

The charging data of interest relates to work-placed charging and from this information there are 486 workplace charging events for individual vehicle users. Those charging events with a rate of charge less than 0.5kW and higher than 50kW were discounted as this does not conform with the charging infrastructure included in the trial (which included a range of slow to rapid chargers). This removed 10 charging events, leaving charging data from 13 vehicles spread across 476 charging events over 207 days. When considering data for weekdays only, Figure 63 shows the distribution of the charging start times and indicates the number of charging events is higher in the morning than later on in the day. There is a clear distinction when the majority of vehicles arrive on site, which is as expected with commuter vehicles due to their arrival at work being in the morning for a typical UK 9am to 5pm work day.

From the ‘journey energy information’ there are 10675 recorded journey events where the vehicle is charged at work by an individual. Those journey events where the speed of travel is below 5mph and above 100mph are considered out of range and therefore discounted as incorrect due to the feasibility of an average journey speed lying outside of these values. 377 events were of zero or negative duration and a total of 10339 journey events were between the accepted speed values. The distance travelled by the vehicles within the data set ranged from 0.2 to 84.7 miles however the mean is only 7.16, suggesting the variance within the data set is large.

To calculate this equation (95) is used as follows;

$$\sigma^2 = \frac{\sum(X - \mu)^2}{N} \tag{95}$$

Where μ is the mean, N is the number of values and X is the data point. This calculates the variance as 73.50, with the standard deviation as 8.57. This demonstrates a large variation within the distances recorded, suggesting that for the simulation it may be difficult to predict the distance travelled for any single simulated scenario.

POOL VEHICLES

There were 2305 work placed pool vehicle charging events for 63 vehicles, 1944 of which occurred at night. 29.37% of these were outside the acceptable rate of charge range of 0.5kW – 50kW, leaving 1628 charging events for 62 vehicles over 160 days. The distribution of charging events for pool vehicles is much broader when compared to the commuter data shown in Figure 63, as fewer charging events occurred in the morning. This is to be expected as the vehicles are left onsite overnight and used during the day, allowing charging to occur when not in use and required.

4717 vehicle journeys were within the accepted average range for speed of 5mph-100mph. The range of distances travelled was between 0.86 and 25.19 miles, a much shorter distance than the commuting vehicles. This is unsurprising, with pool vehicles generally being used for short journeys between sites or for EV demonstration purposes. The mean journey distance is 5.58 miles, with a standard deviation of 5.39 and variance of 28.47. Whilst the variability of the data set is not quite so wide as with the commuter vehicles, the unpredictability of the data is still reasonably large.

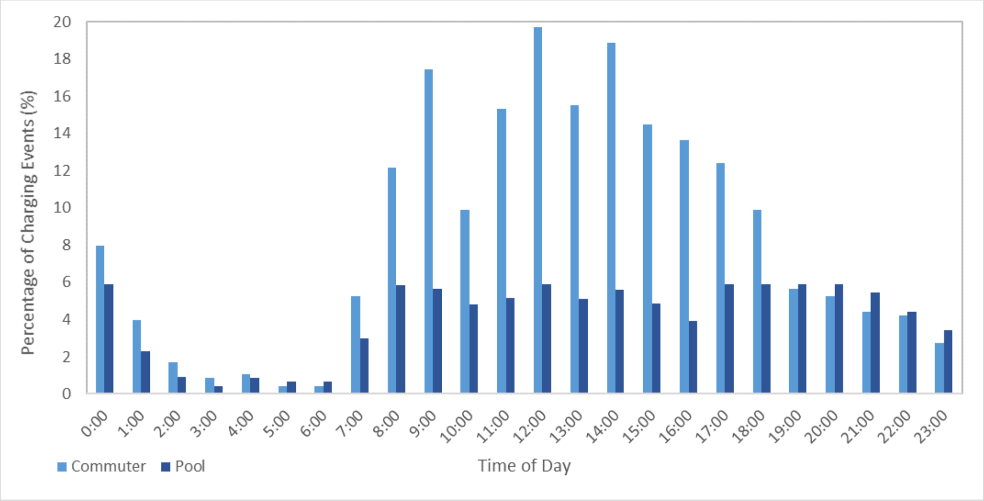


Figure 63 – Commuter and pool vehicle start of charging probability distribution

Average daily profiles for commuting and pool vehicles are presented in Figure 64, showing the number of vehicles present on site during every 30-minute time step over a 24-hour period. This was created by simulating 100 vehicles in the V2GFAE and recording their arrival and departure times over the 24-hour period.

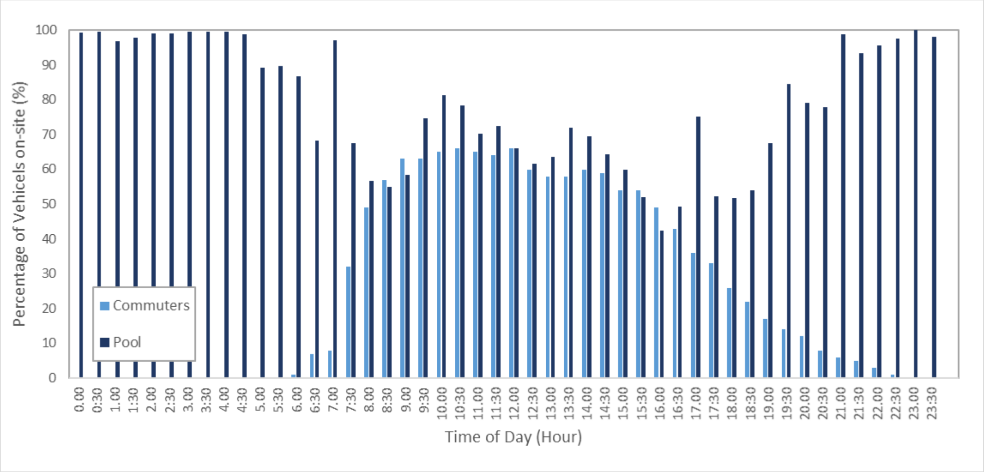


Figure 64 – Number of commuter and pool vehicles on-site profile

The commuter vehicle is very typical of this data set, with the arrival of the vehicle into the system occurring at the beginning of a working day and departure at the end. There are also long durations where a large number of vehicles were present. The pool vehicle profile is much denser, with a number of vehicles present on-site throughout the day. A number of the pool vehicles are present at the site for the entire evening which is in contrast to the commuter vehicles. This would suggest the commuter vehicles would be most suited to peak shaving for local buildings, whilst the pool vehicles would be useful for a variety of alternative applications due to the large number of vehicles present onsite.

5.3.4 STOR MARKET DATA

The data used to simulate STOR dispatch periods is based on information supplied by E.ON and taken from [157]. Pre-set into the model is the ability to set the season and therefore the windows in which STOR requires support. A summary of these windows is given in Table 46.

Table 46 – STOR call out windows [157]

	Season	**Windows**
A	April	07:30 – 14:00 and 19.30 – 22.30
B	May-August	00:30 – 14:30, 16:30 – 18:30 and 20:00 – 23:00
C	September	08:00 – 14:30 and 16:30 – 22:00
D	October	08:00 – 14:00 and 16:00 – 21:30
E	November-January	07:30 – 14:00 and 16:30 – 21:30
F	February-March	08:00 – 14:00 and 17:00 – 21:30

A response and dispatch time are also simulated based upon STOR demand requirements, resulting in a start and end time for EV discharge. Figure 65 shows the average monthly delivery into STOR for 2015. This data was taken from the National Grid (NG) data portal and shows the variation in supply for each month. This correlates with the windows given in Table 46 [158]. Normal STOR operation requires generators to despatch on average 3 times per week, equalling around 155 days per annum.

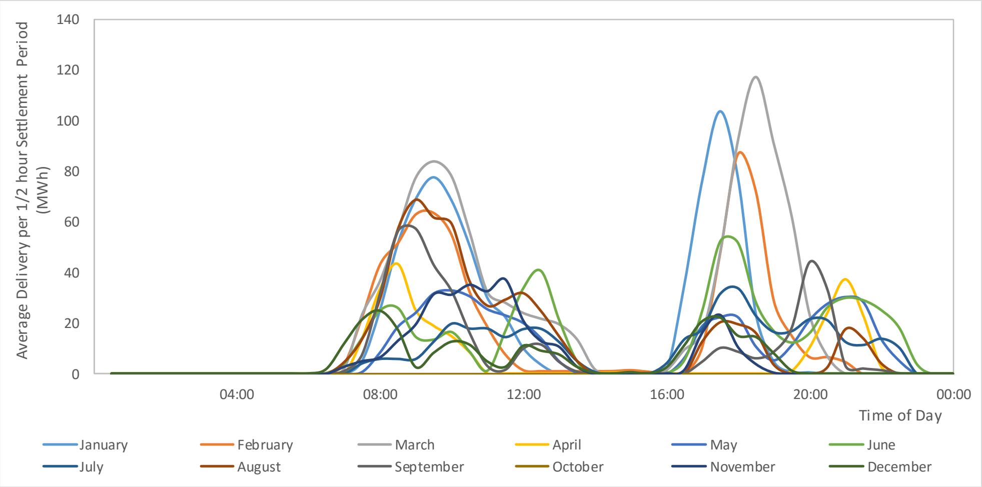


Figure 65 – Short Term Operating Reserve (STOR) average provision per month for 2015 (data from [158]*)*

Figure 65 shows a much higher probability of the vehicles being called to discharge between 8am to 2pm and 4pm to 8pm, which is as would be expected given that all of the call windows populate these times. The provision of energy throughout the day changes based on the day of the week in question, in addition to the variation with month. Figure 66 shows the average utilisation of energy per half-hour period of the day by STOR for weekdays.

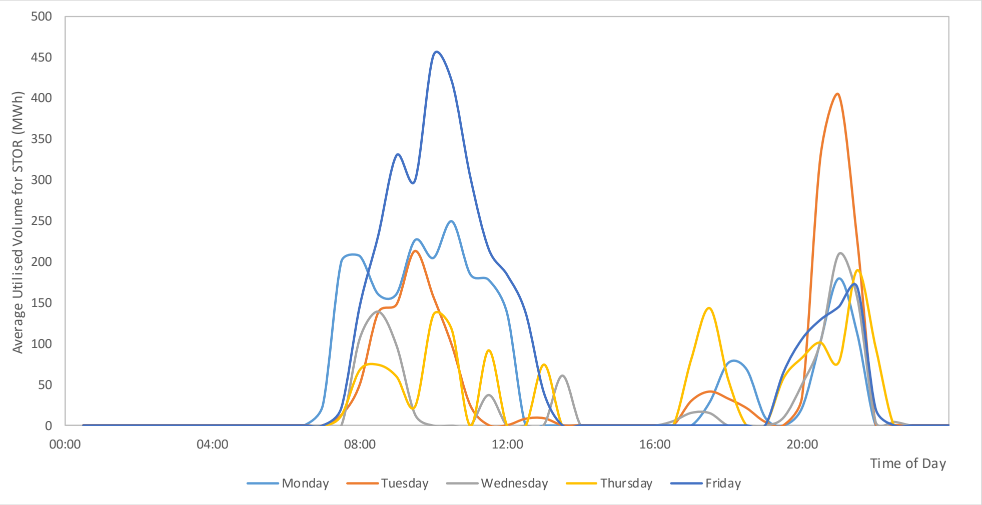


Figure 66 – STOR average delivery volume profile per day (based on data from [158]*)*

In general, the provision peaks follow the same format as given in Figure 65 but disaggregated by day as opposed to month. This gives an indication as to which weekdays would be more likely to have a STOR demand requirement and is important if single day support is of interest within the case study. The income generated from STOR provision has been separated by season and is taken from the NG STOR Annual Market Report for 2014/2015, as shown in Table 47 [159]. When the season is specified by the software user, the corresponding payment tariffs are selected.

Table 47 – STOR availability and utilisation payments (taken from data supplied by [159]*)*

Season	**STOR Availability Payment ($£/kWh^{-1}$)**	**STOR Utilisation Payment ($£/kWh^{-1}$)**
Apr	0.0043	0.1711
May-Aug	0.0043	0.1704
Sept	0.0040	0.1673
Oct	0.0041	0.1673
Nov-Jan	0.0033	0.1712
Feb-Mar	0.0033	0.1713

5.3.5 CAPACITY MARKET DATA

The capacity market is not predominantly an energy delivery scheme, but rather a power availability payment and is an availability contract based on a yearly payment. The auction for 2014 closed at £19.4/kW/year, meaning if the virtual power plant (VPP) were contracted to provide 2MW/year for example, the income would be £38,800 for that year [160]. It is assumed for this simulation that the vehicles are managed by a VPP. The VPP will provide energy from the vehicles to other markets in addition to the capacity market to generate additional income support for energy delivery as opposed to just capacity provision. For the purposes of this analysis, this is assumed to be the half-hour day ahead wholesale energy market.

Bidding into this market is undertaken, as the name suggests, a day ahead of the delivery time and energy delivery for multiple half-hours per day can be provided [111]. For this simulation, upon commencing discharge, the vehicles provide energy for 1 hour and get paid based on the rates given in Figure 67. It is assumed supply will occur at the same regularity as STOR – 155 days per annum to reduce degradation on the EV battery and to provide a like-for-like comparison of the two market scenarios.

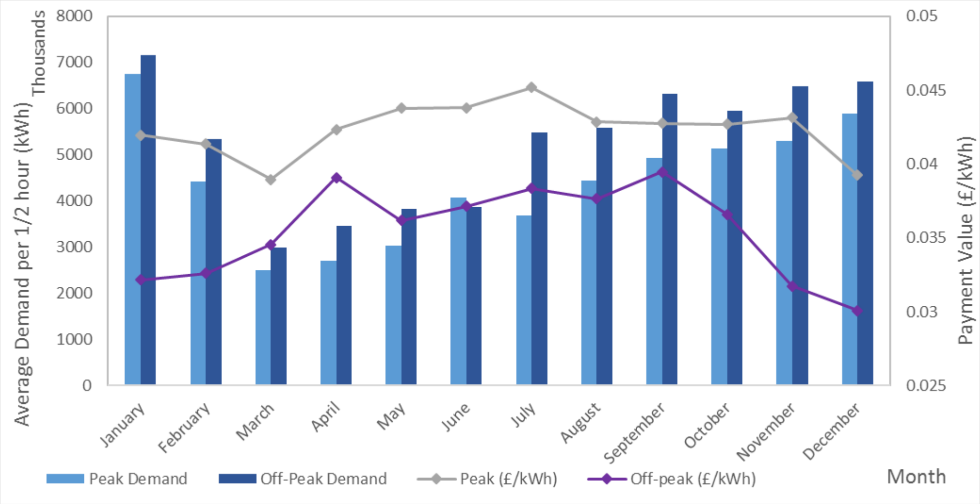


Figure 67 – Wholesale Energy Market demand and price for half hour day-ahead auction (adapted from data supplied by [111]*)*

Looking at income by half-hour period, Figure 68 shows the monthly payment price per MWh of electricity supplied into the market which peaks between 4pm to 8pm. It would be advisable to predominantly bid into this time period in order to maximise profits from energy delivery into this market.

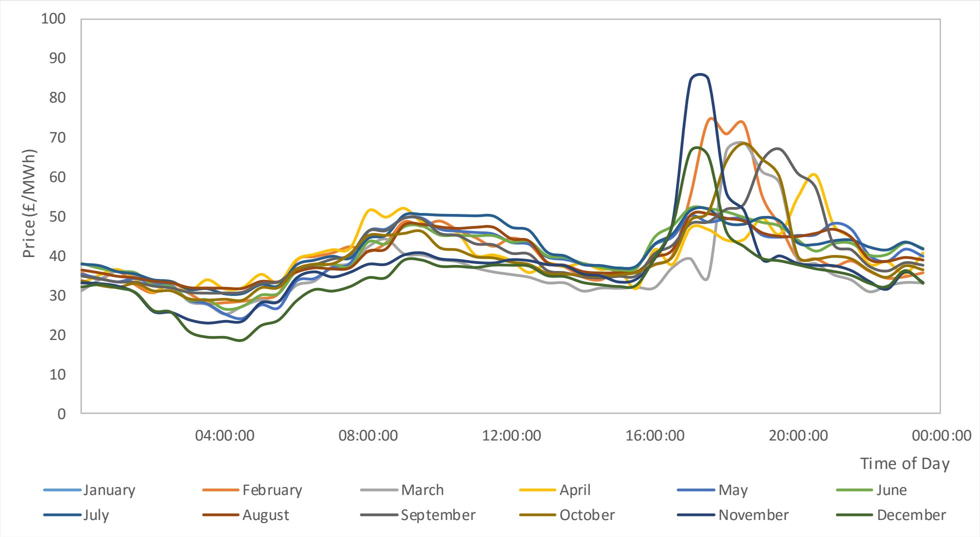


Figure 68 – Price per MWh electricity supplied to half-hour day ahead market per half-hour, demonstrating monthly variation

In order to maximise the profit generation from this market it is suggested the supply profile used for this market is based on a real-life generation profile of pumped hydro storage (PS). Figure 69 shows the UK PS generation profile by month, which correlates with the payment profiles shown in Figure 68, suggesting it is a suitable generation probability model to use to maximise profit generation.

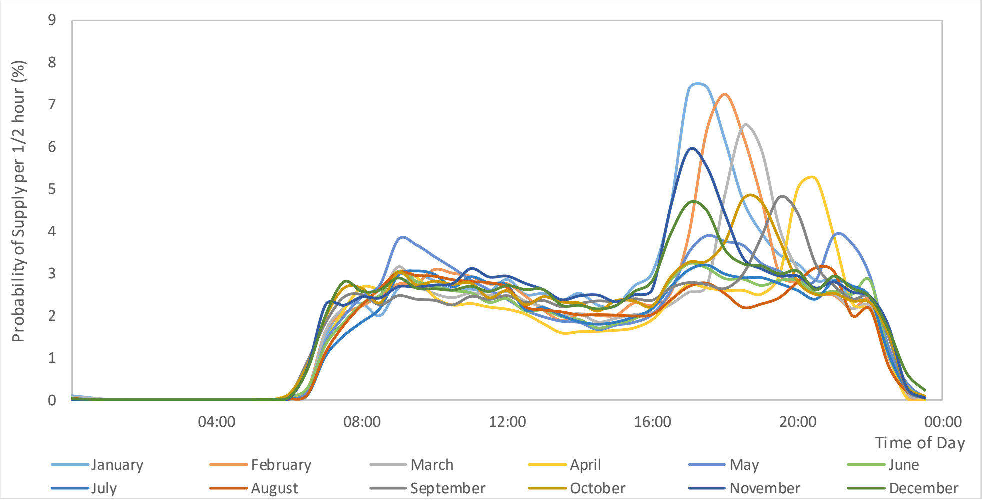


Figure 69 – Energy arbitrage average percentage likelihood of start of generation based on pumped storage (using data taken from ELEXON web portal [161]*)*

5.4 Case Study Review

A preliminary investigation into the potential impact of EVs with V2G at a specific commercial location has been conducted to understand the UK economic potential of V2G based upon vehicle usage profiles, building demand and market potential. Through this preliminary analysis, gaps in knowledge identify the need to conduct detailed analysis into V2G for local building support and within a UK market.

5.4.1 Building Level Evaluation

The local system evaluated is two commercial office blocks at MSP, with 10 EVs simulated at each. The journey profiles for the 10 commuter vehicles were analysed and the average availability per 11 hour working day was calculated as ~68kWh. The discharge rate has been assumed to be 3kW based on a slow charging/ discharging system. The average daily demand profile averaged across a year is displayed in Figure 70 for the two buildings analysed. The discharging schedule takes into consideration availability duration, time of availability and predicted daily availability based upon previous historical data. The impact of discharging these 10 vehicles into the two buildings analysed is shown in Figure 70, where the orange line denotes the reduced energy demand during the 11 hour working day evaluated.

Vehicle owners benefit from providing electricity to the building; whereby in this analysis this payment is assumed to be £0.07/ kWh, which is the average price paid by the building at the time of analysis. Assuming a 6kWh discharge per day, this yields £0.42 per day and equates to ~£107 per annum (assuming 255 day working year). Benefits to the buildings (savings from using energy supplier fed electricity) based on a £0.07/ kWh payment for V2G provided electricity is 68kWh x £0.07 = £4.76 per day. Compared to £0.115 per kWh price from an energy supplier, this represents a saving of ~£780.00 per annum when compared to energy supply electricity prices. Scaling up the distribution to a future EV scenario assuming 100 EVs distributed across the six buildings presents savings to the Science Park of ~£7,800.00 per annum, excluding any payment tariff benefits provided to the Science Park by the distribution network operator (DNO) through reducing grid dependency.

Whilst the analysis does show a clear economic saving to the buildings through utilising excess electricity stored within the vehicles located on site, the income received by the vehicles is very low and does not consider the impact increased cycling of the battery will have on its lifespan and therefore the economic impact. Additionally, the vehicle use profiles generated here are very generic, with each vehicle arriving and departing at the same time and with the same energy available for discharge in each vehicle battery. In order to fully appreciate the extent to which vehicle usage profiles and drive cycles affect EV support opportunities, simulation of vehicle usage information is important to understand real-world driving habits and therefore vehicle battery availability.

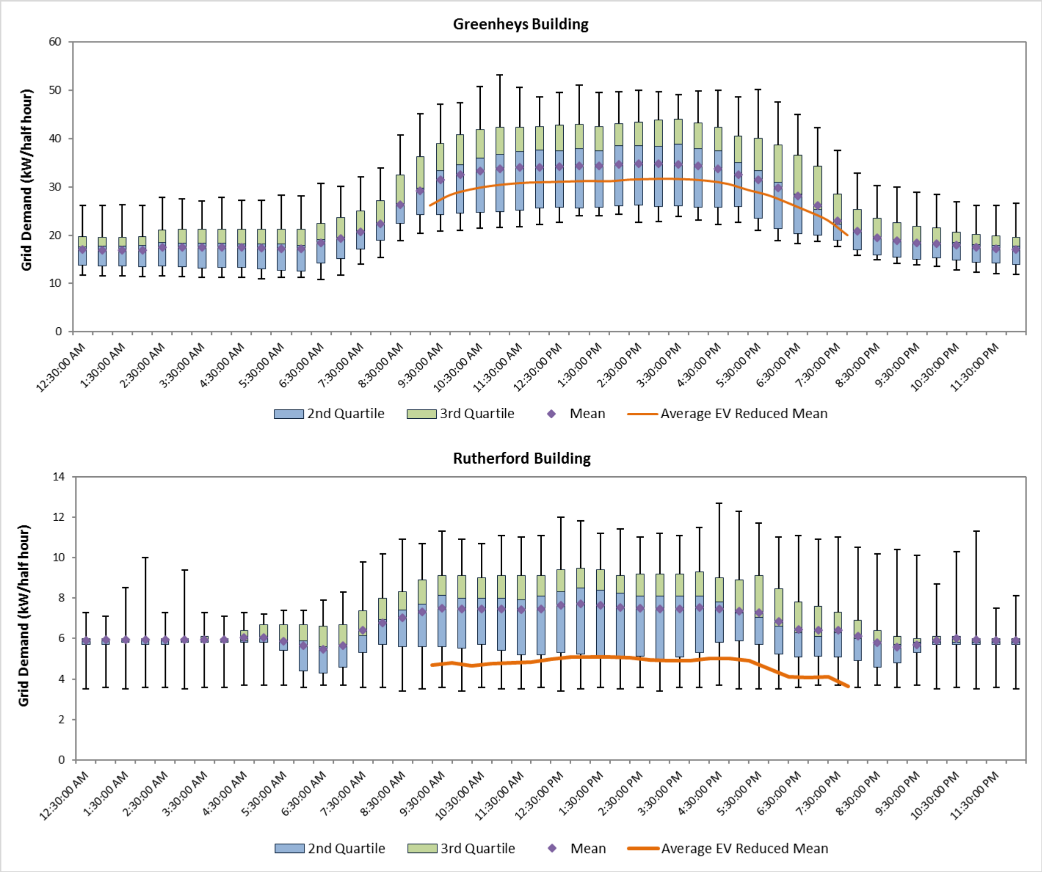


Figure 70 – Daily demand profiles for two exemplar properties at Manchester Science Park

5.4.2 NATIONAL LEVEL EVALUATION

This analysis explores at a high level, the impact multiple EVs across a variety of disparate sites could have on reducing overall national demand and the potential for energy trading. This research was presented at the 5th IET Hybrid and Electric Vehicles Conference (HEVC 2014) by the author [162].

This analysis uses the full vehicle data set as was used for the previous building analysis (where a 10 vehicle sample was taken) and explores the impact privately owned commuter vehicles could have on ancillary service support. Overall evaluation of the data identified an average daily energy use of less than 15% for the private vehicle batteries, suggesting V2G opportunities would be available. Based upon the data evaluated, the average daily vehicle travel duration for private vehicles is ~30 minutes and the distribution of the journeys is given in Figure 71. The journey profile is as expected, with a spike in use between 07:30 – 09:00 and 17:00 – 20:00, suggesting the majority of vehicles were used for commuting to and from work.

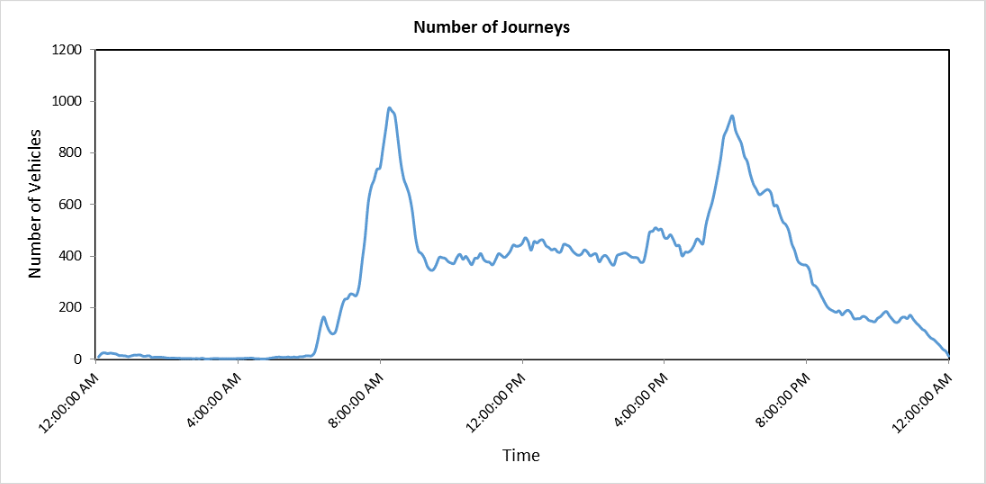


Figure 71 – Vehicle usage profile for private commuter vehicles

For the vehicles analysed, average daily charging demand per vehicle is ~9kWh. Assuming a 25kWh battery capacity for all vehicles types, this leaves a total energy availability of 16kWh. Including an additional 30% to account for any unknown journeys that might occur, the average daily discharge amount per vehicle is 8.5kWh. Taking this energy demand profile and apply it to UK projected EV uptake figures the total UK demand can be estimated for the journey patterns given. UK road vehicle projections for total vehicle numbers and EV numbers are taken from Department for Transport (DfT) statistics and Element Energy respectively and summarised in Table 48[163][13].

Table 48 – UK Road and EV Uptake Figures 2015 – 2030 [163][13]

Year	**Total Road Projection Numbers (millions)**	**EV Projection Numbers (millions)**
2020	37.27	0.68
2025	39.81	4.6
2030	42.35	13.6

In varying the proportion of the total fleet available for grid balancing services, the potential support options for the UK can be evaluated. Current UK electricity demand peaks between 4pm and 8pm on week days. Table 49 shows National Grids (NG) predicted demand figures based on two possible prediction scenarios; "Slow Progression" and "Gone Green" [40]. These refer to slow and renewably assisted scenarios respectively, with the slow scenario indicating a failure to meet CO2 reduction targets by 2020 [40].

Table 49 – UK Electricity Demand Scenarios, 2012 – 2030 [40]

	Slow Scenario			**"Gone Green" Scenario**		
	2012	**2020**	**2030**	**2012**	**2020**	**2030**
Peak Demand (GW)	61.1	57.5	56.7	61.1	59.7	62.7
Annual Demand (TWh)	328	303	297	328	317	323
Total Capacity (GW)	92.3	96.2	115.8	92.3	111.6	153.6

Three different penetration levels have been evaluated for the 2030 vehicle uptake scenario. The first considers the penetration rate depicted by the fleet analysed from the data set. The second increases this by a factor of 100, and the third a factor of 1000 for comparative purposes. The uptake rate of the V2G enabled technology is calculated at 10% of the total EV fleet, with 83.6% of the vehicles being for private use based upon DfT statistics [164]. The total available energy based upon the usage profile evaluated from this study is between 1 and 20GWh, depending upon penetration rate. Assuming the same vehicle availability for market provision, such as Short Term Operating Reserve (STOR), the minimum number of required vehicles over the standard 2-hour call period is just 147. This provides just over 1MW of electricity, including a discharge efficiency of 80%. If the vehicles were paid an example £0.1/kWh for discharge into this market, revenue is in the region of £0.85 per day. Assuming a 3 day per week call out, this equates to ~£130 income generated per annum for each vehicle.

Based on the building and national level evaluation conducted here, albeit at a basic level, there is an indication that EVs in combination with V2G could be beneficial to the UK to alleviate peak demand. However, knowledge of which energy markets or discharge patterns are most suitable is dependent upon a variety of factors including building demand, vehicle usage, vehicle type, renewable generation provision and national UK demand. This suggests a knowledge gap and therefore the potential for development of a platform through which to evaluate suitable EV/ V2G opportunities specific to a case study, validating the importance of the research conducted in this thesis.

5.5 SCENARIO ANALYSIS

This section builds upon the very high level analysis conducted in the previous section by using the V2GFAE software to establish the V2G potential for MSP. This acts to demonstrate the benefit of the software when compared to the conventional, high level analysis conducted previously, along with providing a detailed assessment for MSP. This analysis uses the outputs from the V2GFAE software, both the summary statistics and output data sets for statistical analysis. All results and analysis conducted has been undertaken using the outputs available from the software, demonstrating its flexibility and relevance in generating an understanding of the importance and impact of V2G to the case study selected. A recap of the scenarios built into the software and their functionality are given in Table 50.

Table 50 – Scenario summary table

Energy Support Scenarios	
Scenario B1	Building demand, no PV, vehicles discharge as and when available and required to provide peak shaving to the building. Vehicle number is specified.
Scenario B2	Building demand, no PV, vehicles discharge when available within the specified time of use tariff. Vehicle number is specified.
Scenario B3	Building demand, PV generation, vehicles charge when available and if there is an excess of PV generation. They discharge as and when available and required to provide peak shaving to the building. Vehicle number is specified.
Scenario B4	Building demand, PV generation, vehicles charge when available and if there is an excess of PV generation. Vehicles discharge when available and required within the specified time of use tariff. Vehicle number is specified.
Scenario M1	Vehicles provide energy to the energy market STOR when available and if called upon. Vehicle number is specified.
Scenario M2	Vehicles provide energy to the Capacity Market when available and if called upon. Vehicle number is specified.

Looking at the building demand with the addition of V2G support for Scenario B1 for commuter and pool vehicles in Figure 72, there is a significant difference in the demand reduction experienced by the two vehicle types. The availability profile in Figure 64 of the pool vehicles shows a large data spread, with a number of vehicles being available throughout the entire day as opposed to the commuter vehicles where none arrive before 6am. On the other hand, the pool vehicles are much more sporadic in their support potential, as shown in the bottom image of Figure 72. In running the software for 50 and then 100 vehicles, the variation in vehicle availability is apparent and the commuters provide a much smoother profile versus the pool vehicles.

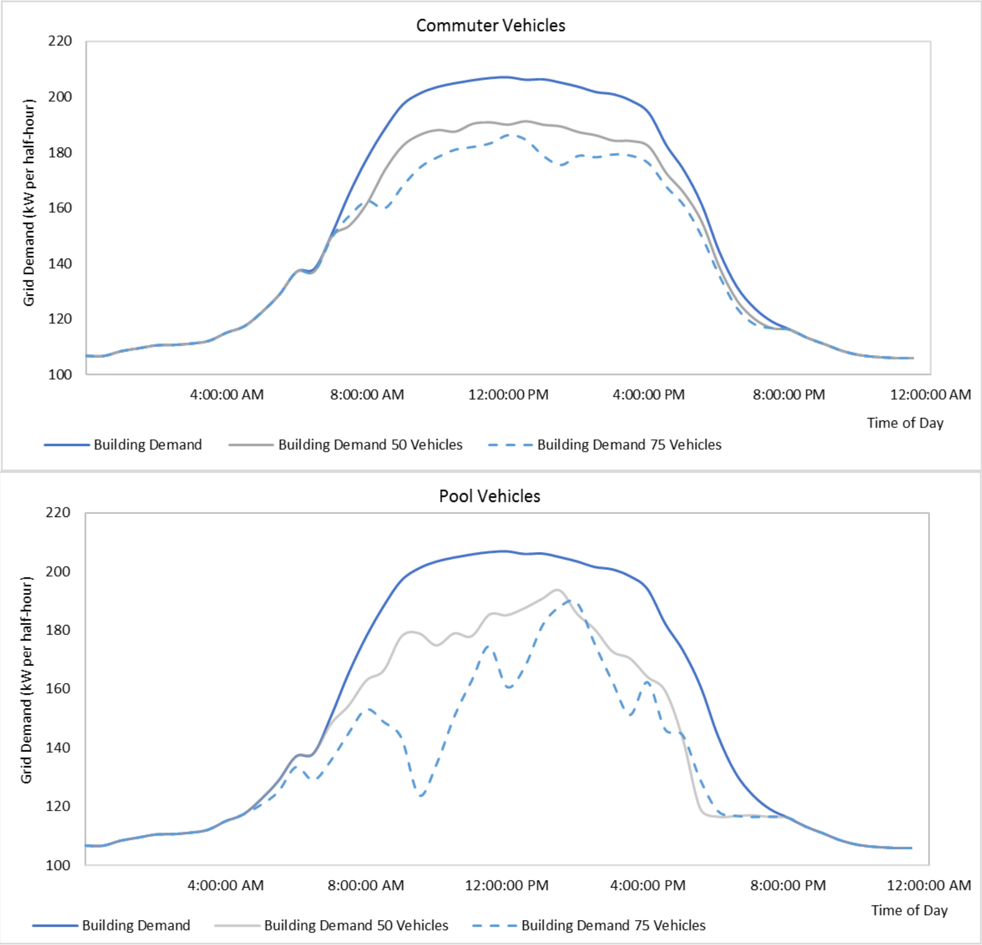


Figure 72 – Comparison of commuter and pool vehicle building demand reduction profile

5.5.1 INFRASTRUCTURE AND ELECTRICITY FUTURE COST PROJECTIONS

Due to the potential opportunity for EVs with V2G to provide some economic benefit to buildings and EV users in the future, it is important to understand at what point infrastructure pricing becomes realistic. By using the equation from a 3kW PV cost curve from 2010 to 2014, an estimated cost reduction in the price of V2G infrastructure can be calculated based on a starting price of nearly £35,000 [165]. The results of this projection are displayed in Figure 73, which takes into account increased demand reducing manufacturing costs and as a result reducing the unit price. It is estimated the V2G units will reach the value equivalent of the costs used throughout the analysis in this chapter (£3750) between year 9 and 10. This value is taken from data obtained by Cenex through the Plugged-in Midlands (PiM) network and is based on a 7kW rated unit with two connection points. Considering the current date this is likely to be around 2023/ 2024, which is a realistic time projection when considering intervention and uptake rates of EVs. However, other factors could influence this including market change and completion. The extremely high starting cost of the reduction curve is based on the price paid for the V2G system installed at Aston University in Birmingham, installed by

Cenex as part of an Innovate UK project, with costs expected to reduce less rapidly as time goes on, as was observed from PV cost curves calculated.

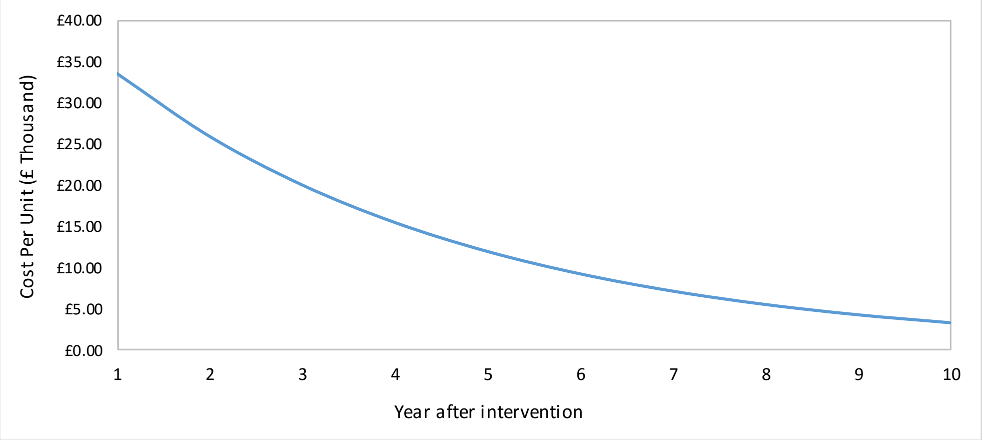


Figure 73 – V2G infrastructure cost projections

Looking at electricity price projections, DECC [11] estimate around a 26% increase to electricity prices due to the impact of environmental policy on small to medium sized business users by 2020. Based on electricity prices taken from [166] and a PV payment price for generation and export taken from [167] and [168] respectively, the estimated figures are given in Table 51. These electricity figures are used in all calculations unless otherwise stated.

Table 51 – Projected Electricity Costs (2020) (based on data from [11] [166] [167] [168][169]*)*

Electricity Rate Type	**Price (£/kWh) Projected to 2020**
Standard Rate	0.186
V2G Tariff Price	0.150
V2G Market Tariff Price	0.30
TOUT Tariff Price (Peak)	0.215
TOUT Tariff Price (Off-Peak)	0.123
Capacity Market Capacity Payment	19.4 (£/kW/year)
PV Generation Tariff	0.0594
PV Export Tariff	0.0485
Night time charging cost	0.100
DUoS base rate (green)	0.0501
DUoS medium rate (amber)	0.0549
DUoS high rate (red)	0.1402

5.5.2 WHAT IS THE SIGNIFICANCE AND IMPACT OF VEHICLE USAGE PROFILES?

Here an evaluation of EV availability for V2G support services is presented, with analysis performed with respect to vehicle availability for the energy scenarios and the impact of discharging EVs into buildings with and without PV generation at MSP. The availability of commuter and pool vehicles for local discharge or energy market provision can be evaluated to establish which scenario suits the vehicle use types with regards to percentage availability. The method by which this comparison is achieved is by running 75 vehicles through each scenario in the software 10 times and recording the number of vehicles available for V2G services for each run. An average is then calculated and the percentage available taken from this average. The values of the input variables are given in Table 52 with the results shown in Figure 74.

Table 52 – Set variables for case study analysis

Variable	Value	Units	Reference
Number of vehicles	75	n/a	n/a
Number of runs	10	n/a	n/a
Battery Limit	40%*	(Of total battery capacity)	n/a
Battery Capacity	24	kWh	Given in Cenex FCRT
Artemis Value (Average)	16.56	kWh/100km	Calculated in Cenex FCRT
Charge Value	0	kWh (charge when below)	n/a
Threshold Demand	0	kW	n/a
Time of Use Tariff	3:30PM – 8:30PM	Given in ½-hour time step	n/a
STOR Season	1	n/a	n/a

* This value has been chosen based on the information gathered during the literature review relating to battery cycling degradation impacts ([73] [74]).

The PV scenarios ranked the highest for the commuter vehicles due to the potential charging and discharging opportunities they present as they had more storage provision than the on-site pool vehicles, meaning their availability was greater. Additionally, the pool vehicles are used during the middle of the day when PV output is highest and therefore their availability is reduced. Surprising was the low availability of the pool vehicles for STOR and Capacity Market services, with just 16% and 14.37% respectively of the vehicles available. This is likely due to the pool vehicles taking many shorter journeys throughout the day, reducing their availability on-site.

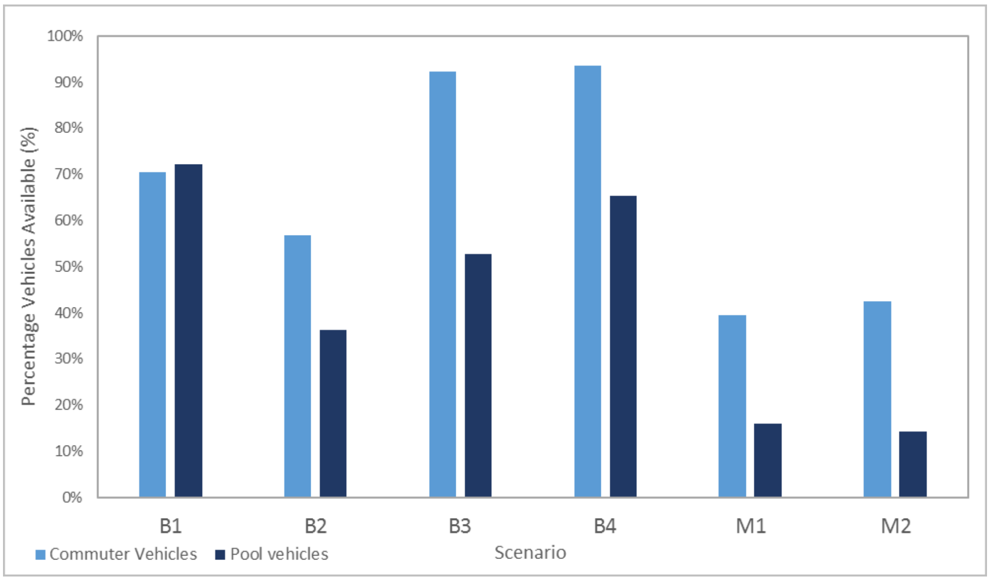


Figure 74 – Comparison of number of vehicles available for each scenario type

This initial analysis suggests commuter vehicles are more suited for V2G scenarios than pool vehicles from an intervention uptake perspective. This is due to the long periods of time commuter vehicles are spent stationary at one location and the shorter journeys made by the vehicles demonstrated in this data set. Whilst availability of the vehicles is essential in enabling them to perform V2G support services, of equal importance is the economic viability of the scenarios to both the vehicle and the building. The following section evaluates the significance of V2G tariff structures and pricing.

5.5.3 WHAT IS THE SIGNIFICANCE OF TARIFF STRUCTURES AND PRICING TO BUILDINGS AND VEHICLES?

The benefit of a vehicle signing up to a V2G scheme is dependent upon the price received for each kWh of electricity supplied for V2G services as the number of EV battery cycles increased due to V2G provision. This must be considered when evaluating the economic benefits of a V2G scenario per vehicle. Commuter and pool vehicles also have different economic cases, assuming the pool vehicles are owned by the building they are located at, the income received by the vehicle is less important than to commuter vehicles as only the degradation costs need be considered.

This analysis uses an average daily demand profile for the Science Park and an average July day for the Enterprise Building as case studies to evaluate the minimum price required by the vehicles per kilowatt-hour (kWh) of electricity supplied. The Science Park has an extremely large demand profile throughout the day, meaning a large number of vehicles could be utilised for V2G services to reduce overall building grid demand. This is in contrast with the Enterprise Building, that has a relatively small demand profile and with the addition of PV generation, exceeds demand during parts of the year. Income generated by the Science Park through employment of V2G technology is calculated as both a daily average and through Net Present Value (NPV) analysis later on in the chapter. Evaluation of the different scenarios establishes the variation in cost savings experienced for scenario type. Initially a set of variables are defined at the outset of the analysis, as presented in Table 53.

Table 53 – Set variables for case study tariff pricing analysis

Variable	Value	Units	Reference
Number of runs	10	n/a	n/a
Number of Vehicles	50	n/a	n/a
Battery capital cost	4000	£	[170]
Battery capital cost (£/kWh)	160	£/kWh	[170]
Number of battery cycles – driving	3000*^{1}	-	n/a
Number of battery cycles – V2G	1020*^{2}	-	n/a

*^{1}The number of drive cycles is based on an assumed annual mileage of 15,000 miles per annum, equalling 60,000 miles over four years as taken from the Cenex Fleet Carbon Reduction Tool (FCRT) figures.

*^{2}The number of V2G battery cycles is calculated based on 255 V2G cycles per annum, equalling 1020 cycles over 4 years.

5.5.2.1 OPTIMAL VEHICLE INCOME EVALUATION

Figure 75 displays a comparison of energy supplied and income required for scenarios B1 and B2 for the Science Park and M1 and M2. Income to the vehicle relates to the minimum tariff required by the vehicle per kWh of electricity supplied to break even. This takes into account the increased cycles on the vehicle battery due to V2G energy provision and the depth of discharge, as demonstrated in Chapter 4 Section 4.7- Cost Model 7. It is important to note that with the case of the aggregated Science Park demand, the PV generation is never high enough to create an excess of electricity and therefore Scenario B3 and B4 have not been considered as they will operate in the same way as Scenarios B1 and B2.

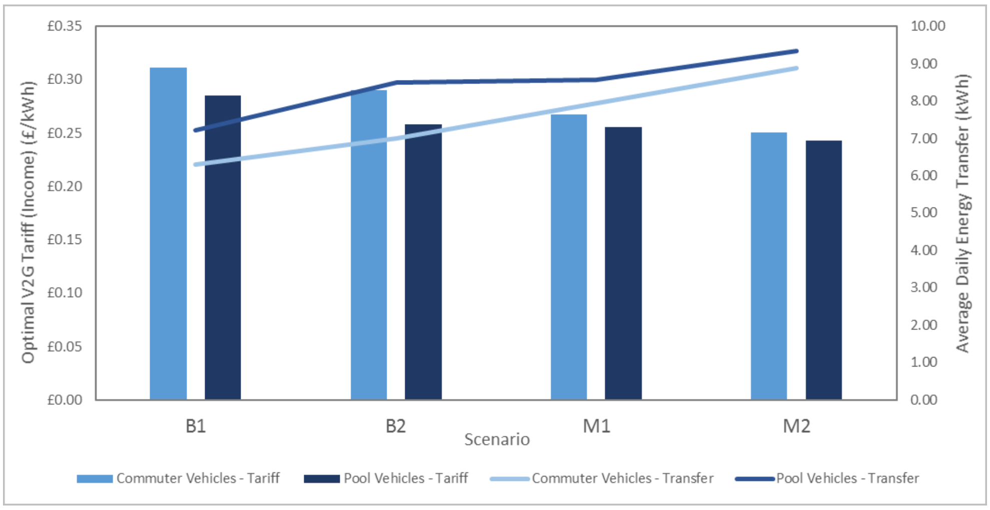


Figure 75 – V2G minimum required vehicle tariff for the aggregated Science Park building demand, STOR and the Capacity Market

Looking at the results in Figure 75, those vehicles where more energy transfer is achieved, generally yield lower payment requirements. This is as a result of greater utilisation of the battery due to a deeper depth of discharge and therefore greater income generated for each battery cycle performed. The pool vehicles yielded more energy for all four of the scenarios than the commuters, resulting in a reduced optimal V2G tariff. In general, all four of the scenarios had similar results for the two vehicle types, with the average optimal tariff for the commuter and pool vehicles being £0.28/kWh and £0.26/kWh respectively. It is important to note that this optimum tariff price includes the cost of re-charging the vehicle battery.

Running the same analysis for the Enterprise Building during an average July day with PV and only 25 vehicles, the results in Figure 76 indicate the impact charging from PV has on the financial suitability of V2G for the vehicles. Scenarios B3 and B4 represent a significant increase in the optimal V2G tariff required by the vehicles. These values are considerably higher than the electricity tariff payments paid by the building to its energy supplier and therefore renders Scenario B3 and B4 unsuitable support options for the Enterprise Building. This is due the low storage opportunities offered by the vehicles as a result of short journeys and therefore small amounts of energy consumed on a daily basis for travel purposes. This in turn reduces the capacity of the vehicles for storage provision. Overall, pool vehicles are used more and this correlates with the energy transfer figures represented below.

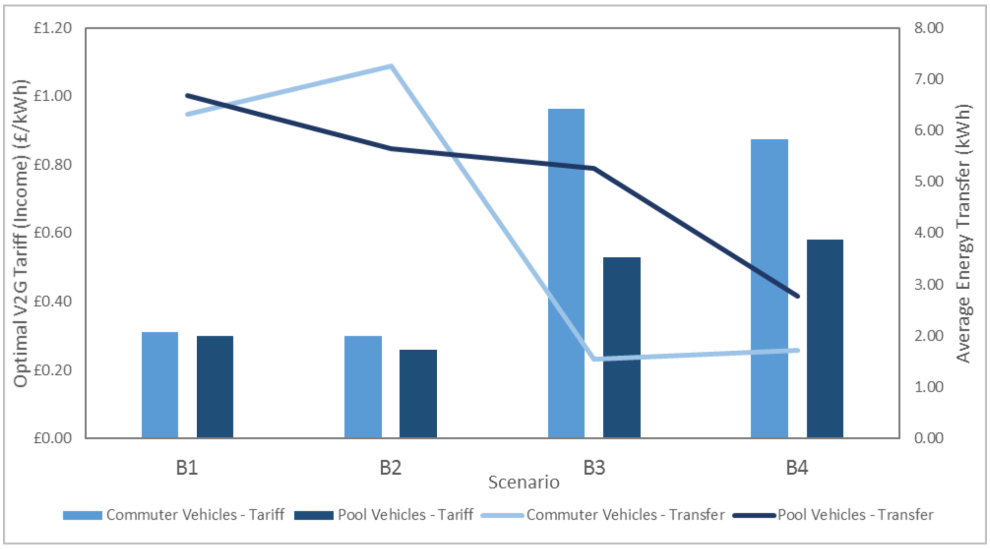


Figure 76 – V2G minimum required vehicle tariff for the Enterprise Building

In reality, the pool vehicles will not be required to make a profit, only to receive enough economic benefit to outweigh the degradation on the battery caused by V2G cycling (be cost neutral). The high costs associated with the PV scenario indicate that V2G is unlikely to be a suitable support option for buildings with such a low overall demand deficit.

In order to promote V2G uptake with commuter vehicles, it is assumed the vehicle owners will require a profit to be made through utilisation of their vehicle battery. For example, a £0.02/kWh increase in payments from the baseline breakeven requirement (as given in Figure 75 and Figure 76) will produce an annual income of ~£50, assuming ~10kWh is discharged per day for 255 days a year. A £0.05/kWh increase yields ~£130 per annum of additional income. However, with pool vehicles owned by the building owner, the cost implications are different, with the minimum V2G payment to the vehicle being sufficient to ensure the combined company assets generate a cost reduction so long as building cost savings are achieved.

The calculated yearly vehicle income based on the costs given in Table 51 are displayed in Figure 77, which are calculated based on the net profit after the degradation costs are considered. The optimal minimum tariff for all scenarios is above £0.24/kWh, meaning that the building scenarios with vehicle payments of £0.15/kWh are automatically rendered unsuitable due to the £0.10/kWh charging requirement. If the vehicles are charged for free, for example from excess PV generation then a small income could be achieved.

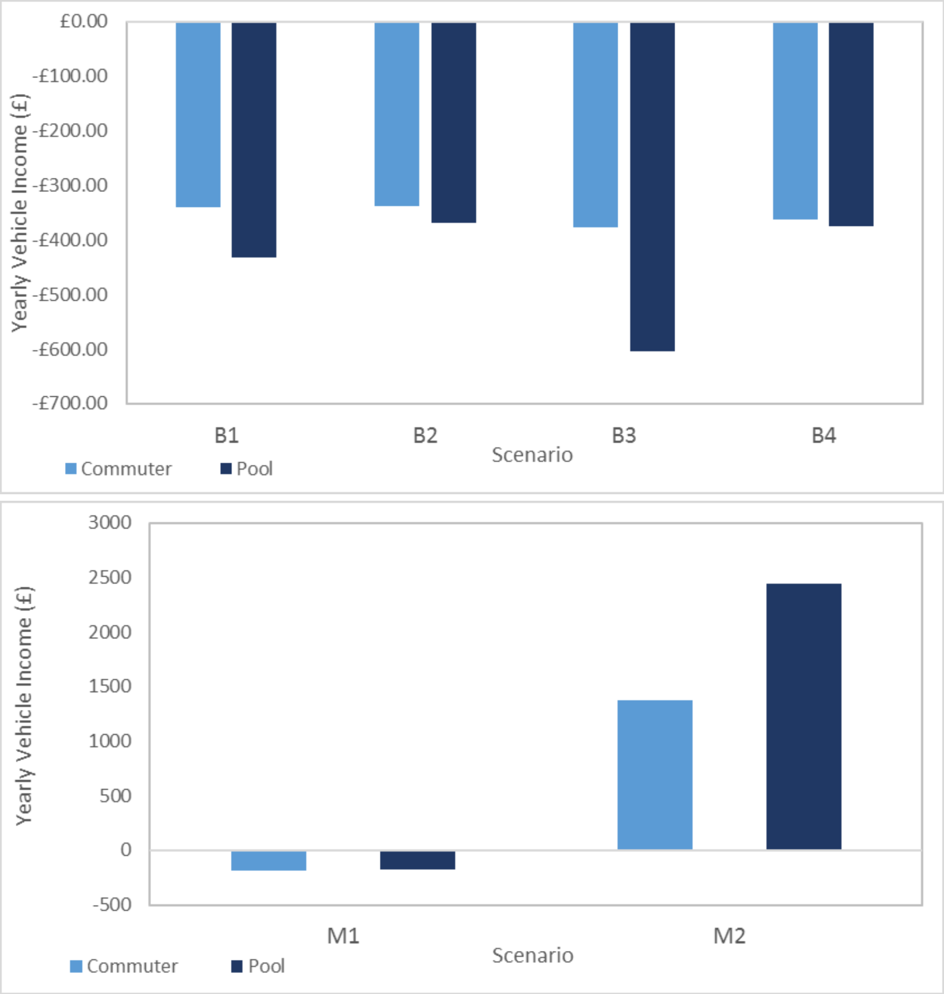


Figure 77 – Average yearly vehicle income from each energy scenario (scenarios B1-B4 top, scenarios M1 and M2 bottom)

For STOR, the vehicle income is calculated using a baseline power availability payment and an energy provision payment. The income calculated for scenario M2 indicates that the combination of the Capacity Market with the wholesale electricity market has the potential to offer huge income generation (circa £2000 per annum) if vehicles are available for a number of provision days a year. Whilst this does not include infrastructure costs, the anticipated yearly income from provision of energy for just 155 days per annum indicates that even with the infrastructure costs, income generation is still possible (see section 5.5.4 for infrastructure calculations).

The results from this analysis demonstrate the benefit of commuter and pool vehicles in signing up to a virtual power plant (VPP) aggregator to provide energy for market provision. The building based scenarios seem to present no benefit to the vehicles, however the next section will evaluate if there is significant economic benefit in utilising V2G to offset building grid demand.

5.5.2.2 BUILDING SAVING EVALUATION

The benefit to a building or collection of buildings, such as the Science Park, in utilising V2G is to yield an electricity cost reduction. Using the average aggregated Science Park and an average July day for the Enterprise Building as examples, the estimated daily saving to the building is calculated using a baseline of 50 vehicles for the Science Park and 25 for the Enterprise Building. The results are given in Figure 78 for the Science Park and Figure 79 for the Enterprise Building. The aggregated Science Park demand with the addition of PV does not drop low enough for vehicle charging from PV to be a consideration. Therefore, only Scenario B1 and B2 are explored, as with the analysis in the previous section.

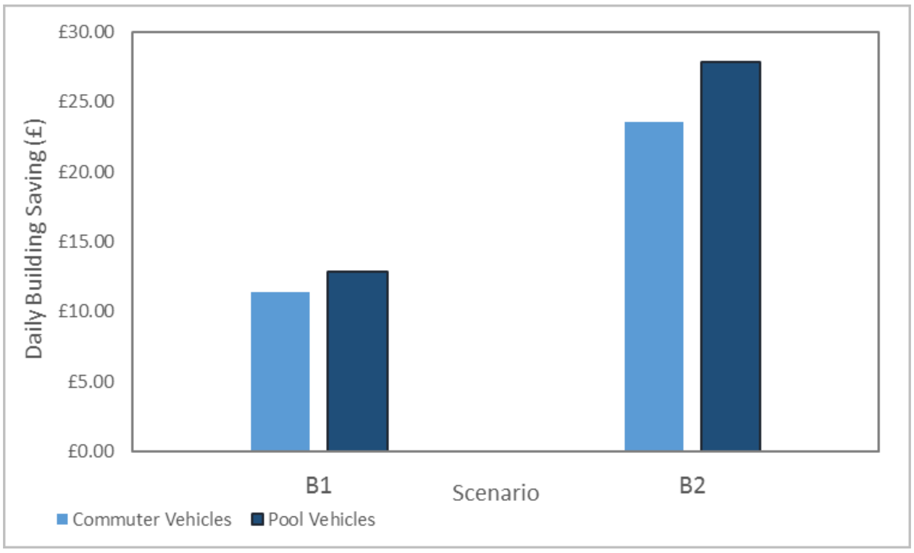


Figure 78 –Manchester Science Park average daily savings with V2G intervention

From Figure 78 the first observation is that both scenarios produce positive building savings from V2G provision based on V2G payments of £0.15/kWh. Scenario B2 produces a considerably higher daily saving than Scenario B1 due to the higher TOUT. In discharging the vehicles during this peak demand time, the building is making a daily saving of around £25. Aggregated up this equates to around £6,375 per annum, when discharging 50 vehicles over 255 working days a year. Whilst in section 5.5.2 it was suggested pool vehicles would be less available for V2G services, those that are available provide the greatest economic income for the building, producing around 18% more income generation than the commuter vehicles.

With the Enterprise Building (Figure 79), again pool vehicles generate a greater income for the building, with Scenario B2 producing the greatest daily saving at £11.06, equating to £2,820.30 per annum. However, considering the requirement for commuter vehicles to make an additional saving on top of the break-even point, the building savings from pool vehicle utilisation outweighs commuter vehicles even more. The PV based scenarios present little or no benefit to the building as the excess energy stored in the vehicles is assumed not to generate income from feed-in tariff (FIT) payments for export. Additionally, the energy stored in vehicles during the day from excess generation is not always discharged back into the building as some vehicles may leave before building demand becomes high enough to require discharge back again. It is likely that higher building demand would yield more economically viable results.

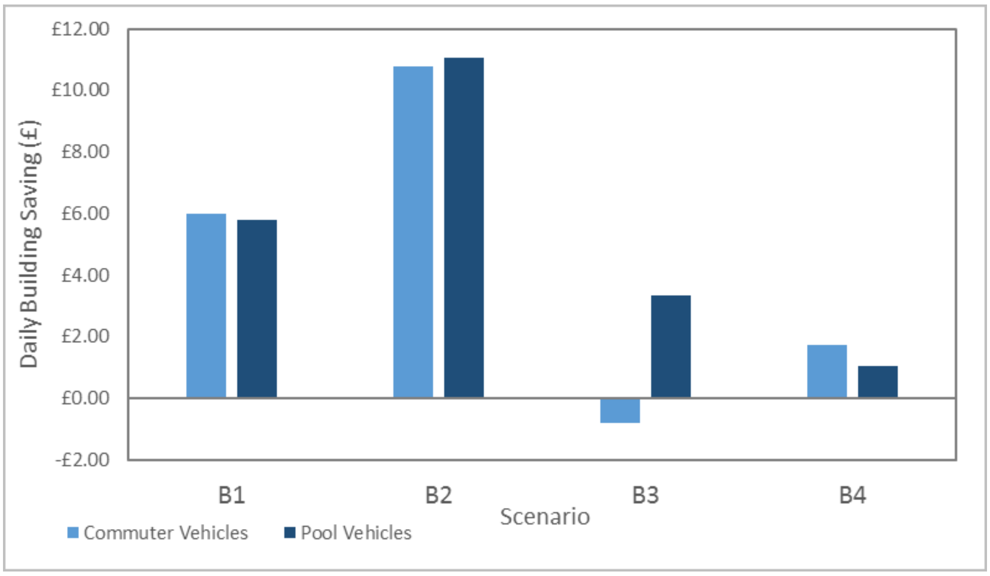


Figure 79 – Enterprise Building average daily savings with V2G intervention

Overall, the aggregated demand of the Science Park benefits more from the integration of V2G based on this analysis as the daily income is larger due to the significantly higher demand profile and therefore more opportunity for vehicle discharge. In addition, the size of the Science Park means the vehicle parc is much larger and therefore the number of vehicles available across the site for V2G services is likely to be large. These savings are based upon an assumption that infrastructure is pre-existing as there is already a requirement to charge vehicles during the day, for example the pool vehicle fleet. The impact of infrastructure costs to profit generation is discussed in more detail in Section 5.4.4.

5.5.2.3 TRIAD ECONOMICS

Mentioned earlier was the charging scheme the Science Park operates under, paying an increased electricity price for energy consumed during the triad periods. To calculate the potential economic savings received by MSP through utilisation of V2G during the triad periods, the three triad days for

2014/2015 (Table 54) are simulated through the V2GFAE and the electricity costs shown in Figure 80 applied as follows;

A. Initially the maximum demand for each of the triad periods shown in Table 54 are taken from the Science Park data and added together.

Table 54 – Triad periods for 2014/2015 [171]

Day	Time Period
04/12/2014	17:00 – 17:30
19/01/2015	17:00 – 17:30
02/02/2015	17:30 – 18:00

$$Total\ Triad\ Demand = 197.151 + 224.236 + 209.407 = 630.794kW$$

B. This value is then multiplied by the loss adjustment factor, which is taken as 1.051 [172].

$$630.794\ x\ 1.051 = 662.964$$

C. Using the half hourly zonal tariff taken from [173], this is multiplied by the previous value to calculate the total triad charges for 2014/2015.

$$Total\ Triad\ Charges = 662.964\ x\ 33.78 = £22{,}394.92$$

Running the aggregated data from MSP through scenario B2 to specify the triad period, the cost savings can be calculated based on a cost value of ~£35.50/ kWh during the triad periods. The maximum rate of discharge is 24kW and the system discharges vehicles until the building demand reaches the minimum demand value and the process stops. This requires an average of 30 vehicles. The calculated economic benefit in utilising EVs for demand reduction yields very positive results, with an annual cost decrease of £12,793.02. It should be noted that it is not a straightforward task of simply reducing demand for those three periods as it is not easy to know exactly when the triad periods might be. MSP employ a triad forecasting software to provide them with relatively accurate predictions of when the triad periods might be.

It would also be beneficial to also utilise the vehicles to offset the peak demand costs on days that do not have triads. Looking at the payment profile of the Science Park for the remainder of the year in Figure 80, there is some potential benefit in utilising V2G during the peak tariff charge, which is between 4:30pm – 7:00pm inclusive. The price increases to just over £0.175/kWh during this peak demand period and if the vehicles are charged during the cheap day and night time tariffs, further economic reductions could be achieved. Using the 30 pool vehicles to provide this demand reduction, the cost savings for the Science Park per annum equals £1,454.60 on top of the triad demand reduction, giving a total saving of £14,247.62 per annum excluding infrastructure costs.

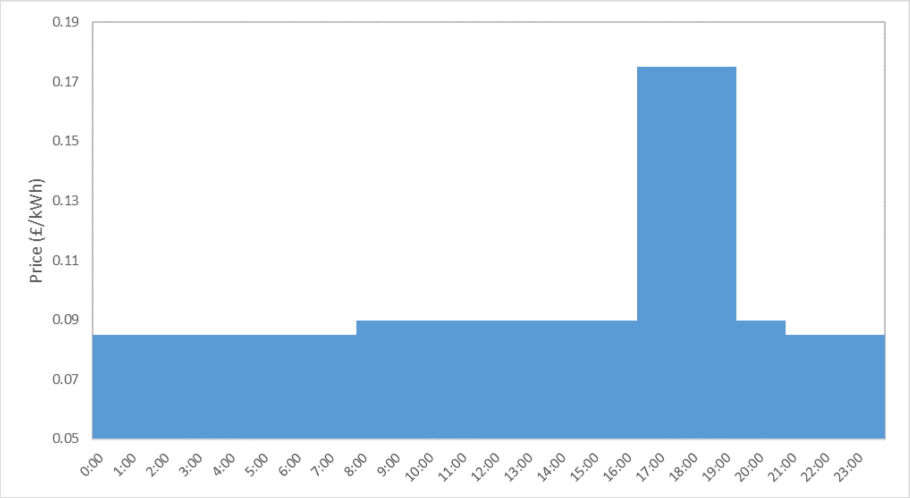


Figure 80 – Manchester Science Park tariff charges and schedule (taken from [172]*)*

Including the additional cost of the V2G infrastructure which is summarised in Table 55 (taken from Plugged in Midlands data), this takes the yearly savings down to £3,514.28, which still proposes potential investment opportunities for the Science Park. More information as to the impact of infrastructure costs on overall affordability of V2G is given in the following section.

Table 55 – V2G infrastructure pricing for triad evaluation

Variable	**Value**	**Units**	**Reference**
Installation Cost	4,000	£ (for post 1, £500 thereafter for each additional post)	Cenex PiM data
Infrastructure Cost	10,000	£ (per post)	Cenex PiM data
Number of vehicles per charging post	2	n/a	Cenex PiM data
Installation lifetime	15	Years	Cenex PiM data

5.5.4 WHAT IMPACT DOES THE PRICE OF VEHICLE-TO-GRID INFRASTRUCTURE HAVE ON THE ECONOMIC VIABILITY OF VEHICLE-TO-GRID AS A WHOLE?

This section performs two purposes; a) to evaluate the price of V2G infrastructure and the impact this has on the tariff price received by the vehicle and b) evaluate this with respect to current EV charging infrastructure. The analysis considers both pool and commuter vehicles and all the scenarios available within the V2GFAE and the variables set as seen in Table 56. The electricity prices are those given in Table 51. Infrastructure installation costs are taken from data obtained through the Plugged-In Midlands network, previously managed by Cenex. The incremental cost increase per additional unit for installation is estimated to be £500 based on this data. This installation price is based on the estimated cost of installing one 7kW double outlet, ground mounted unit.

Table 56 – Set variables for analysis 5.4.3

Variable	Value	Units	References
Number of runs	10	n/a	n/a
Time of Use Tariff	3:30PM – 8:30PM	Time	n/a
Installation Cost	3,500	£ (for post 1, £500 thereafter for each additional post)	Cenex PiM data
Infrastructure Cost	3,750	£ (per post)	Cenex PiM data
Number of vehicles per charging post	2	n/a	Cenex PiM data
Installation lifetime	8	Years	Cenex PiM data

Using the infrastructure optimisation cost model developed within the V2GFAE, the optimum infrastructure price is calculated for each scenario for both pool and commuter vehicles. This value is based upon the calculated optimal tariff price for the vehicles to make a profit from V2G provision (as discussed in Section 5.4.2.1). The building data used is the same as with previous analysis.

Table 57 – Optimal infrastructure price for MSP and the Enterprise Building

Scenario	Aggregated Science Park		Enterprise Building	
	Commuter Vehicles	Pool Vehicles	Commuter Vehicles	Pool Vehicles
B1	-£6,056.89	-£5,455.63	-£6,046.59	-£5,808.16
B2	-£4,030.24	-£2,763.35	-£5,226.18	£0.00
B3	n/a	n/a	-£9,779.46	-£6,742.58
B4	n/a	n/a	-£8,682.87	-£7,764.78
M1	-£4,078.54	-£3,593.88	n/a	n/a
M2	£5,450.00	£5,450.00	n/a	n/a

All of the scenarios evaluated for both the Science Park and the Enterprise Building had negative optimal infrastructure pricing except scenario M2, where infrastructure costs are covered by the Capacity Market payments and therefore show a positive value. The actual infrastructure price (including installation) is £4,390, which falls below the cost requirements for scenario M2. In terms of building related scenarios, it is clear that building support from V2G is only economically viable when building electricity costs are high, as with the triad scenarios. To calculate the average daily savings to the building with the additional cost of infrastructure, 50 vehicles are simulated for the Science Park and 25 for the Enterprise Building, with the installation costs as described in Table 56. The anticipated daily income is presented in Figure 81 for the Science Park and Figure 82 for the Enterprise Building.

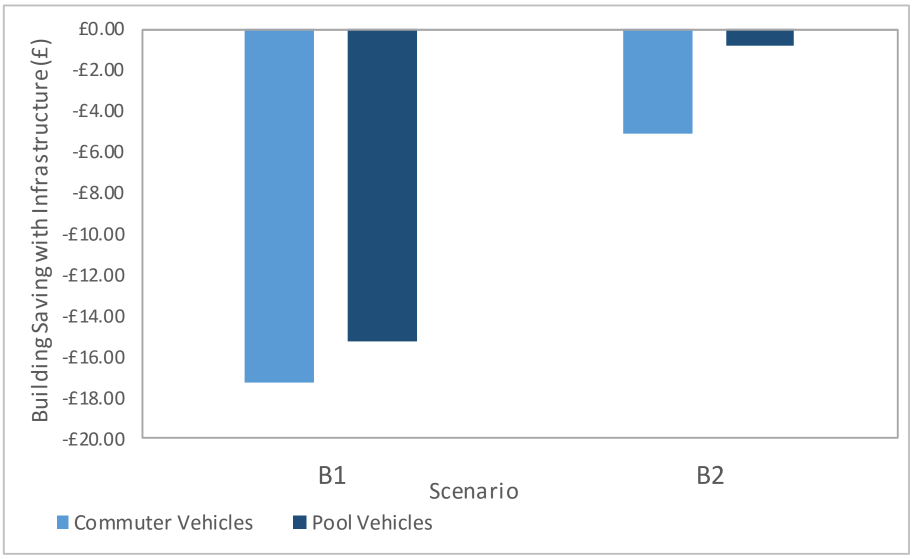


Figure 81 – Manchester Science Park average daily savings with infrastructure costs

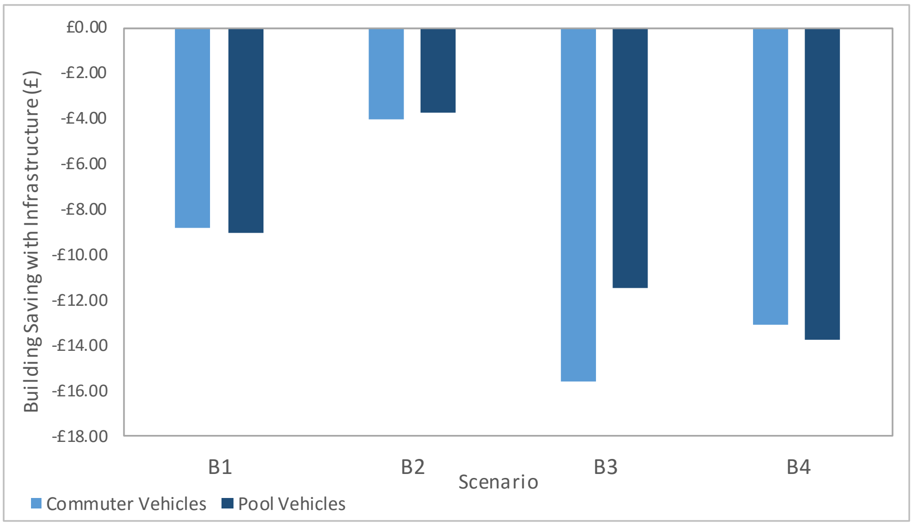


Figure 82 – Enterprise Building average daily saving with V2G infrastructure costs

This analysis supports the results demonstrated in Table 57, with all scenarios producing a negative or zero cost saving for the buildings evaluated. This indicates that unless infrastructure is either pre-existing or being installed to serve a dual purpose (as both a charging point and for V2G services), there is little economic case for V2G at MSP except for triad demand reduction, where a greater economic benefit was observed.

Considering energy market support, the impact of installation costs on vehicle income from support of scenarios M1 and M2 are displayed in Figure 83. The cost of infrastructure outweighs the income generated from energy provision for STOR market support, however as the cost of infrastructure is covered by the capacity payments for scenario M2, a modest yearly income can still be expected.

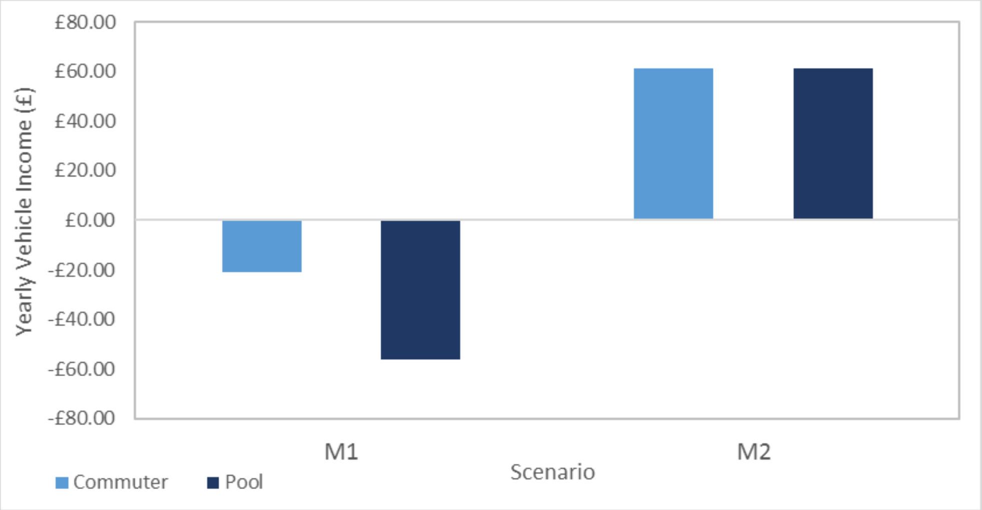


Figure 83 – Energy market scenarios average yearly vehicle income with infrastructure costs

In general, infrastructure costs could be outweighed if the infrastructure will also be used for regular vehicle charging and therefore installation is a pre-existing requirement. However, an additional consideration is the cost of network upgrading. If required, network upgrading due to an increased load/ demand as a result of increased vehicle numbers can be significant and in the region of £100k - £1M. It is impossible to predict this cost without a site survey, as each system will be unique and this could therefore be considered a limitation of this research.

5.5.5 Discounted Cash Flow Analysis

Whilst average cost calculations give a representation of daily income over the intervention period explored, a true indication of the economic viability of the system is through Net Present Value (NPV) and Present Value. This enables the system user to identify the year in which a return on profit can be expected, both with and without infrastructure costs. This section covers present value analysis, exploration into the sensitivities surrounding the NPV and evaluation of uncertainty and variance within the model.

NPV is calculated as follows;

$$NPV = \frac{C_F}{(1-D)^Y} \tag{96}$$

Where; C_F = cash flow, D = discount rate and Y = year.

Here, 50 pool vehicles for the Science Park and 25 for the Enterprise Building are used for analysis over a 25-year period, relating to 25 and 13 charging points respectively. These are assumed to be installed in blocks of 5 over a 5-year period and replaced after 15 years. This means infrastructure costs and electricity prices will decrease and increase respectively over the 25-year period. The cost parameters are summarised in Table 56, with cost projections being calculated from Figure 73 for infrastructure and extrapolated up from Table 51. The NPV is calculated for all scenarios and triad support with a discount rate of 10% which should account for the relatively high risk of the technology. The results of the analysis can be seen in Figure 84 and Figure 85 for building scenarios and Figure 86 for market scenarios, showing present with and without infrastructure costs. All income generation is related to either building income for scenarios B1 to B4 and triad evaluation and the VPP for scenarios M1 and M2.

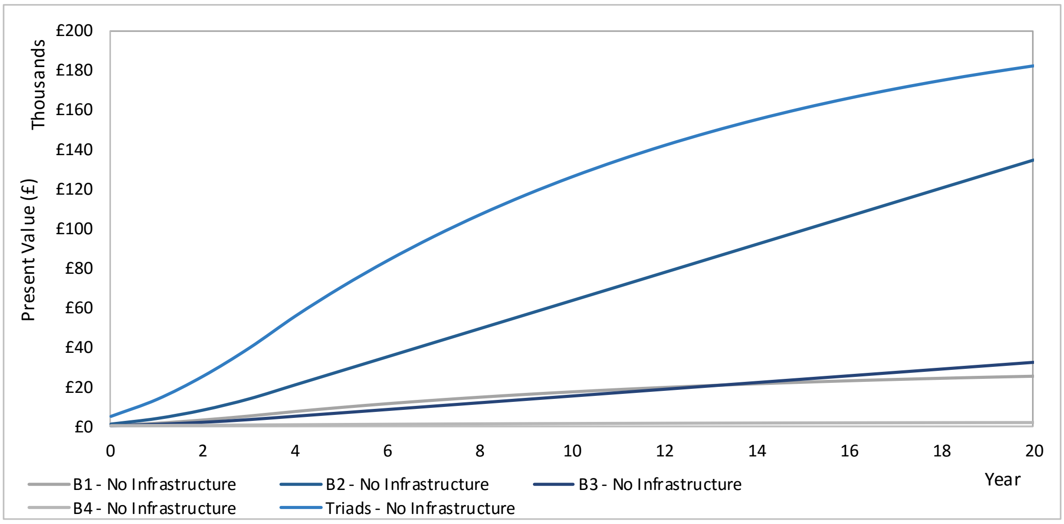


Figure 84 – Present Value analysis for building based scenarios including triad demand without infrastructure costs

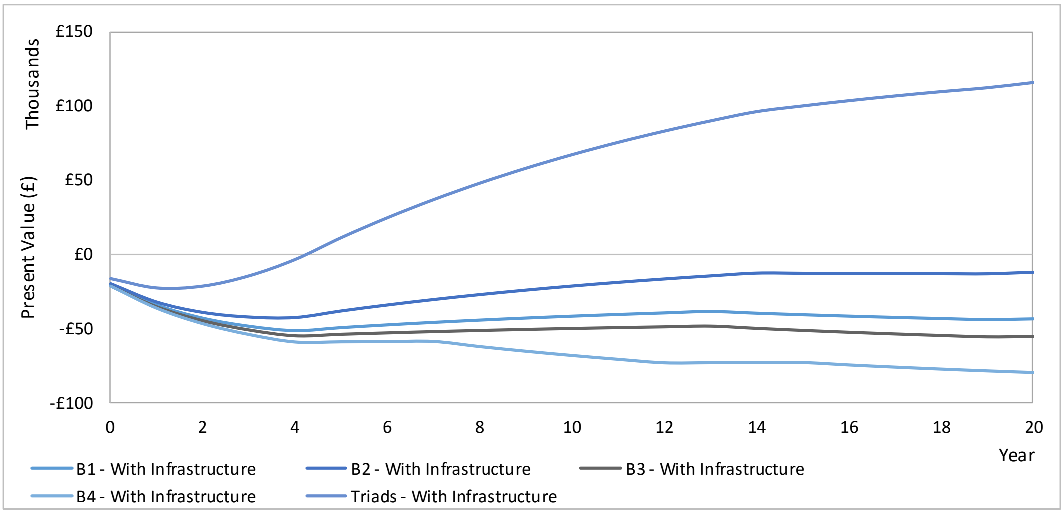


Figure 85 – Present Value analysis for building based scenarios including triad demand with infrastructure costs

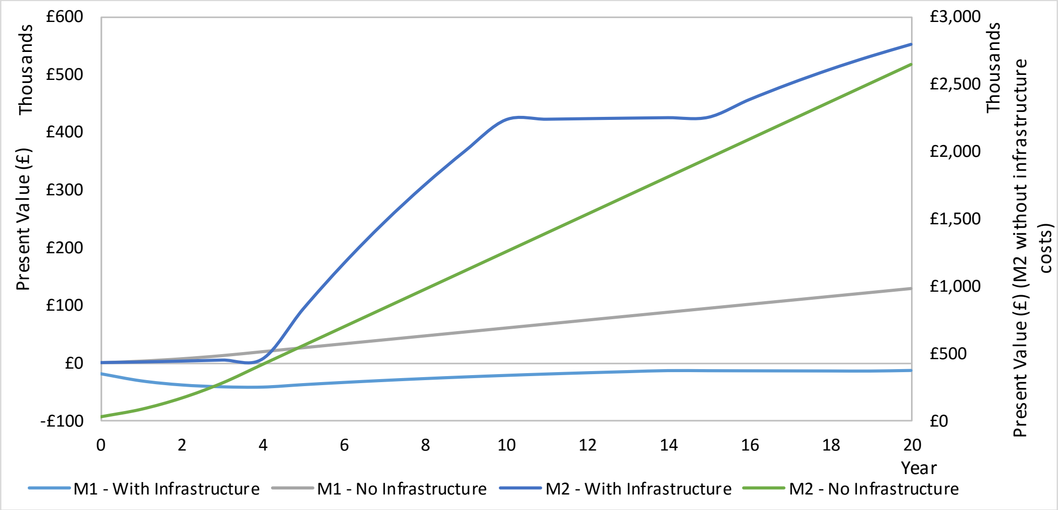


Figure 86 – Present Value analysis for M1 and M2 with and without infrastructure costs

Evaluation of all the scenarios indicates that triad demand reduction and scenario M2 provide the only real economic benefit to the buildings if the costs of installing the infrastructure are also considered. Without installation costs, all scenarios are appropriate, however the capacity market with wholesale trading (M2) provides a substantially increased income over all other opportunities. This is due to the income received for power capacity installation and the additional payment for energy provision to the wholesale market.

5.5.5.1 HANDLING UNCERTAINTY AND VARIANCE

Due to the Monte Carlo based approach to the V2GFAE, variation within the software exists at the vehicle model level, resulting in variation within the outputs experienced by the software. This section seeks to evaluate this variation and the sensitivities surrounding the economic viability of the case study within the evaluated energy scenarios.

The results obtained in the previous sections relate to values calculated by running a number of simulations and then taking an average in order to establish vehicle income, energy transfer and so on. However, in order to ascertain the potential variation within these results, it is prudent to evaluate the variation around these average values. 100 vehicles have therefore been simulated for Scenario B1 and M2 so as to examine the distribution of energy transferred and the corresponding income generation requirements. Figure 87 demonstrates the variation in energy transferred for Scenario B1 – building self-consumption and the related price per kWh of energy transferred.

The distribution of the discharge values is quite broad, ranging from 5.19kWh to 22.47kWh over a 24-hour period with a mean of 10.63kWh. The corresponding minimum payment requirements are also given and are represented by the second axis and the dark blue line. As is expected, as the energy transfer per V2G cycle increases, the minimum payment required by the vehicle for each kWh of energy transfer decreases, with the average being £0.26/kWh. The distribution of energy transfer is not normal, following an almost beta distribution for percentage likelihood of energy transfer. As this distribution type is often used to describe probability distributions, this is not unexpected as a result of the probability distribution sampling performed in the V2GFAE. In addition, a number of factors influence the amount of energy discharged per vehicle, including vehicle availability, duration of stay and building demand.

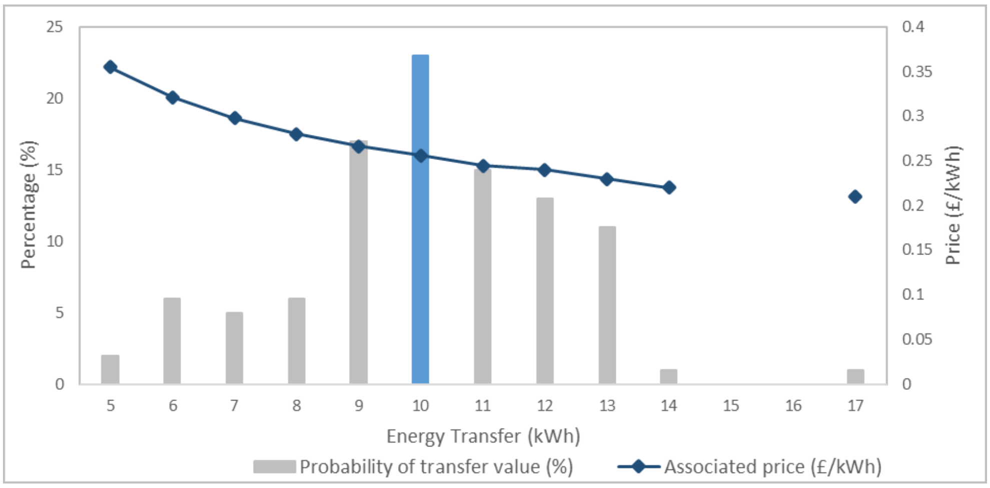


Figure 87 – Scenario B1 vehicle energy discharge distribution and associated kWh payment

The results of the same analysis for Scenario M3 are given in Figure 88. The average transfer value is 11.5kWh which is slightly higher than for Scenario B1. The same correlation is evident with regard to increased energy transfer reducing the payment amount required by the vehicle. The range of energy transfer values is greater for Scenario M2 than B1, however overall the profiles are relatively similar in both cases.

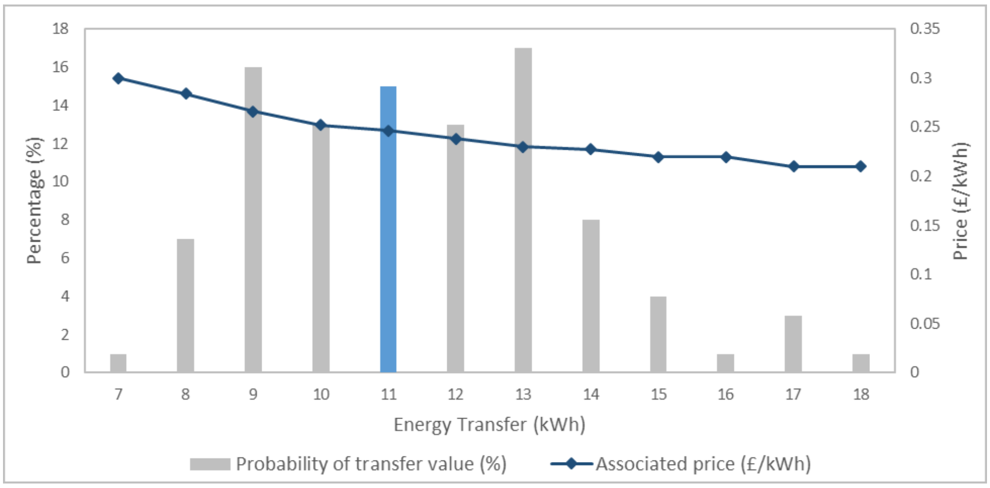


Figure 88 – Scenario M1 vehicle energy discharge distribution and associated kWh payment

For Scenario B1, all of the vehicles require a minimum payment greater than the standard rate grid tariff payment of £0.186/kWh due to a £0.10/kWh charging cost. However, all of the vehicles in

Scenario M2 would be suitable for V2G services due to the high payment per kWh of electricity received from the market. This is something to be aware of when exploring the potential for V2G.

The variance and standard deviation of the data evaluated in the two scenarios here is calculated using equation (97) which is used for the sample data sets and is given in Table 58. This shows a higher variance for Scenario B1 than M2, resulting in a higher standard deviation.

$$\sigma^2 = \frac{\sum(X - \mu)^2}{N - 1} \tag{97}$$

Both data sets are within 3 standard deviations of the mean, implying that the mean values used throughout this evaluation are indicative of the overall data population based on the sample data used.

Table 58 – Data variance and standard deviation for Scenario B1 and M1

Scenario	**Variance**	**Standard Deviation**
B1	6.18	2.49
M2	5.20	2.28

This indicates the data variation and standard deviation are relatively predictable due to the data simulation structure created through the V2GFAE. This is in contrast to the original vehicle datasets for both the commuter and pool vehicles which have a very large variance and standard deviation, meaning the software reduced the uncertainty within the input datasets.

The potential income generated through utilisation of V2G services is subject to variability. To identify where the greatest sensitivities lie, assessment of the NPV for a 10-year period is undertaken on Scenario B2 and M1 as examples. Each of the input variables relating to the scenario evaluated are increased and decreased by 20% and the NPV re-calculated each time. The variation in the NPV from the baseline value is demonstrated in Figure 89 to Figure 91 in the form of tornado plots. The variables used for the analysis are given in Table 59, with the original and altered values for comparison.

Table 59 – Sensitivity analysis variables

Variable	**Units**	**100%**	**-20%**	**+20%**
EV charging payment	£/kWh	0.05	0.04	0.06
V2G tariff payment (B2)	£/kWh	0.15	0.12	0.18
V2G tariff payment (M1)	£/kWh	0.30	0.24	0.36
TOUT peak payment	£/kWh	0.215	0.172	0.258
V2G STOR payment	£/kWh	0.293	0.2344	0.3516
STOR availability payment	£/kWh	0.011	0.0088	0.0132
Total MW provision	MW	3000	2400	3600
VPP vehicle number	-	3000	2400	3600
Infrastructure cost	£	3750	3000	4500
Installation cost first	£	3500	2800	4200
Installation cost sub	£	500	400	600
Installation lifetime	Years	15	12	18
Number of days per annum (B2)	Days	255	204	306
Number of days per annum (M1)	Days	155	124	186
Number of vehicles	-	15	12	18

The greatest sensitivity for scenario B2 lies with electricity tariff payments, with the larger the payment tariff for the grid supplied electricity to the building, the greater the savings achieved by the building through V2G intervention. This results in the second greatest sensitivity lying with the infrastructure cost, where the lower the payments, the greater the economic savings are to the building. Interestingly, reducing the price of the installation of the units has less influence on income than would be expected, with the tariff income displaying virtually the same sensitivities as the infrastructure cost.

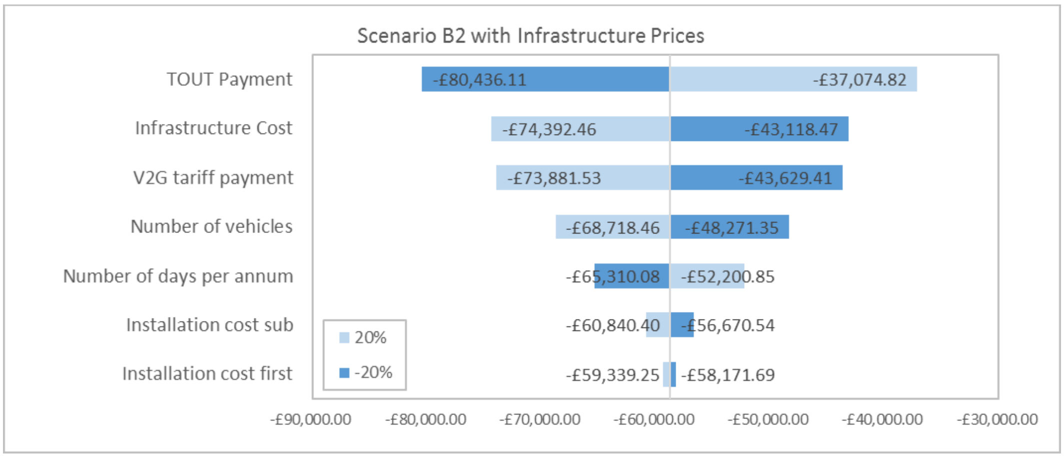


Figure 89 – NPV sensitivity analysis for Scenario B2 with infrastructure pricing

However, if the cost of infrastructure is removed, the income generation and overall NPV for the building becomes much more viable. Figure 90 demonstrates the NPV for scenario B2 without the addition of infrastructure costs. The greatest sensitivities still lie with the grid electricity import tariff and vehicle income payment, with the NPV increasing by as much as £21,680.64 if tariff payments were to increase.

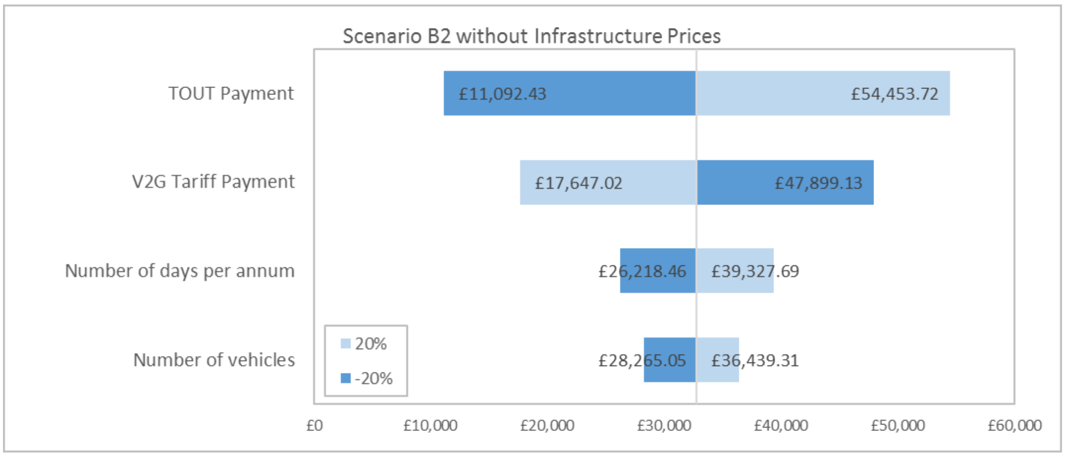


Figure 90 – NPV sensitivity analysis for Scenario B2 without infrastructure pricing

Analysis of scenario M1 (STOR provision) looks at the NPV of a single vehicles income over a 10-year analysis period. The greatest sensitivities for vehicle income are surrounding the payment received by the vehicles for V2G provision for STOR. However surprisingly, the number of provision days has a much greater impact on this scenario than with the building related income. Changing these variables does not have much of an influence on the overall economics of the scenario, demonstrating the key influences to be the vehicle income.

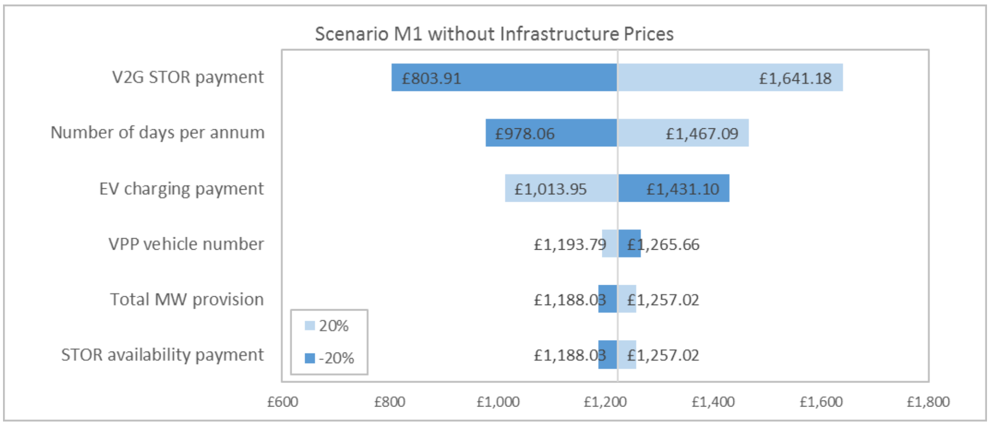


Figure 91 – NPV sensitivity analysis for Scenario M1 with infrastructure prices

This sensitivity analysis has demonstrated the importance electricity tariffs to V2G income generation has on the variation in potential income for V2G led energy support scenarios. Whilst the cost of infrastructure presented little variation within scenario B1 and B2 (where infrastructure was included), the overall income is negative. Key observations from this analysis indicate the importance of the vehicle payment tariff to the ultimate success of V2G. The greater the disparity between the grid imported electricity payment and the vehicle V2G payments, the greater the expected income generation from V2G provision.

5.5.6 WHAT IS THE ANTICIPATED CARBON OFFSET FROM VEHICLE-TO-GRID IMPLEMENTATION?

This section explores the estimated environmental impact the use of V2G could have on overall UK emissions. Whilst out of scope in terms of the V2GFAE and interests of Cenex and the thesis objectives, it is important to understand the carbon impacts increased battery cycling might have on UK emissions. Two elements of the system are considered for their carbon intensity; embedded emissions and short and long run emissions factors, as defined below. These consider both the CO_2 emissions from creation of the V2G or battery systems and the emissions from daily charging/ discharging and the potential carbon offset or cost.

The evaluation will take the form of a comparison from a baseline case study for commuter vehicles in which EVs operate without V2G and charge at the place of work during the day. The carbon emissions associated with this case study will be evaluated and then compared to the V2G case study, in which vehicles are charged at night and discharged during the day for peak shaving. The CO_2 emissions from performing both case studies will be calculated using the following emissions data;

1. Embedded emissions – this relates to the carbon emission in creating the vehicle and the charge post/ V2G unit. The value for the carbon life cycle for the vehicle itself is taken from the Low Carbon Vehicle Partnership report *'Life cycle CO_2e Assessment of Low Carbon Cars 2020-2030'* [174]. Information relating to the infrastructure is more complex, with little information relating to charging infrastructure. Nonetheless, Lucas et al. [175] conducted research into the carbon emissions associated with a variety of transportation fuel types including gasoline, diesel and electricity. The values are summarised in Table 60.

   Table 60 – Embedded EV carbon emission factors (adapted from [174]*)*

Vehicle Type	**Top Level Impact**	**Battery Contribution**
Full EV	24.46 tCO_2e	18.6%
Charging Infrastructure	1.56 g/kWh CO_2e	-

   Assuming a 50 vehicle intervention rate, the embedded emissions calculates as 2198tCO_{2e}, including 25 charging posts.

2. Short run emission factors – these relate to the carbon emissions associated with the national grid. They are taken from analysis conducted by Hawkes [176] into the marginal increase to the grid based upon an increase in demand for the specified fuel type. The values are summarised in Table 61.

Table 61 – Marginal emission factors for UK grid (taken from [176]*)*

Fuel Type	**Emissions kgCO$_2$/kWh**
Coal	0.90
CCGT	0.405
Oil	0.956
Wind	0.00
Nuclear	0.015

Based on the fuel emission values in Table 61 and using the net grid increase through performing V2G activities (due to increased charging requirements), the fuel emissions increase was calculated. The yearly emissions are calculated based on a 255-day intervention per year. The results are given in Figure 92.

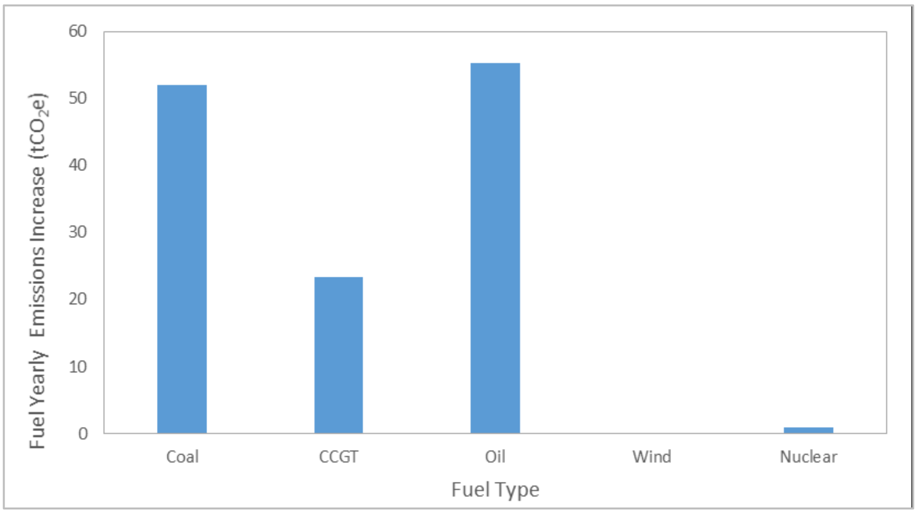


Figure 92 – Total short term yearly emissions increase

Given the increase in charging demand for V2G discharging provision and efficiency factor of the vehicle battery, the overall environmental impact from V2G peak shaving provision is negative if EV charging is performed by any of the fuels listed other than wind.

The total marginal emissions factor for the UK was calculated by Hawkes [176] for 2002 to 2009 as 0.69 kgCO2/kWh which leaves a total of 39.77 tCO$_{2e}$ per annum from the V2G cycling of just 50 vehicles.

3. Long run emission factors – these figures are more complex to determine due to the increased requirement to provide future projection analysis of grid carbon emissions. Nonetheless, Hawkes [177] undertook research to determine the size of emissions reductions due to increased renewable and nuclear generation into the UK grid mix. Hawkes calculated the long run marginal emissions factor to be in the region of 0.26 – 0.53 kgCO$_2$/kWh by 2025 and 0 kgCO$_2$/kWh by 2035 [177]. Based on these values, by 2035 the impact of increased utilisation

of EVs for V2G services will cause little or no negative impact to increasing carbon emissions, resulting in a carbon saving for the UK grid with increased battery utilisation.

5.6 CHAPTER SUMMARY

A variety of energy scenarios have been run against building demand and PV generation data to provide a comparison of the economic benefits from each scenario to the vehicles and building. Comparison of both commuter and pool vehicles was also conducted to demonstrate any performance and economic benefits from either fleet. Additionally, comparison of two very different demand profiles was conducted, using the aggregated demand of the Science Park and an average daily July demand for the Enterprise Building. This demonstrated the impact building demand has on the performance characteristics of the vehicles and therefore the overall performance and economic benefit to the building. A number of building electricity tariff options were considered for MSP to identify if other scenarios to their existing triad charges would be more suitable for V2G provision.

Results from the PV charging/ discharging models for the Enterprise building demonstrates that due to the very low building demand during the summer months, only a small number of vehicles were needed for V2G services, with very little energy transferred. Due to seasonal variation in PV generation throughout the year, the EV support requirements vary considerably. During the Summer months when there is more PV generation, EV support requirements relate to both storage and capacity availability, as opposed to Winter months where the predominant requirement is excess energy capacity for battery discharge. However, storage provision is minimal due to the short commuting times of the vehicles and therefore low energy consumption. Vehicles with greater storage capacity or longer journeys would benefit more from the excess of PV generation. It is therefore suggested this scenario would be better suited to pool vehicle where the state of charge throughout the day is likely to be lower and charging the vehicles from excess PV generation will provide an economic saving as opposed to just reducing the export value. However, comparison of the overall economic benefit from the aggregated Science Park demand and the single demand of the Enterprise Building indicates buildings with large demand profiles receive greater economic benefit than those with relatively low peak shaving requirements.

There is clearly a sensitivity surrounding the infrastructure costs and tariff pricing and their impact on the economic viability of V2G. The functionality of the V2GFAE software allows the users to evaluate this sensitivity and generate an infrastructure price based upon an optimum V2G tariff and vice versa. In evaluating MSP as a case study, the full functionality of the software was demonstrated.

From the analysis relating to percentage availability it was evident that vehicle use type played an important role in the suitability of a vehicle in providing specific V2G services. Whilst PV related scenarios proved to have the highest support in terms of vehicle numbers, when exploring the energy transfer and vehicle utilisation it is clear more suitable opportunities for vehicles are general peak shaving, tariff provision and market support. Whilst the number of vehicles available to provide energy is lower, the income generated is more beneficial to the building and the vehicles in turn. Additionally, when the cost of the infrastructure installation is considered, only the cost savings experienced for triad support provided economic justification for the technology installation. This would suggest that unless pool vehicles are already located on-site, creating an existing need for EV charging, there is little economic justification for V2G provision. This was expressed both in the NPV and infrastructure analysis.

Both energy markets provided some economic benefits to vehicles providing energy services, however the cost of infrastructure left the STOR market analysis negative once costs had been included. In addition, scenario M2 with the capacity market and wholesale market trading was only made viable due to the capacity payments for infrastructure. The economics of this model only work if capacity payments can be assured for a prolonged period of time, otherwise infrastructure costs are not included and income generation could also become negative. Infrastructure cost projections based on existing technology cost curves indicates the values set within the analysis relating to V2G infrastructure are realistic within the developmental timescales considered. Whilst currently expensive, projection of a £3,750-unit price within 10 years correlates with PV projection pricing and current charging point costs.

Battery costs associated with an increase in battery cycling due to V2G clearly play a pivotal role, with an increase in battery cycling increasing the associated costs and therefore increasing the required income from V2G provision. Greater utilisation of the EV battery cycling reduced the price required per kWh, with an increase in discharge per vehicle increasing the affordability of the solution to the building. Calculation of vehicle income indicated that only the market support scenarios provided a significant income generation for the vehicles. Building support opportunities provided no benefit to the vehicles due to the high degradation costs associated with V2G and the cost of re-charging the vehicle after V2G support.

Whilst the economic savings experienced through V2G provision are evident, less evident is the environmental impact increased battery cycling will have on the UK energy grid. Through the analysis conducted in this chapter it is evident there are no carbon savings experienced as a result of peak shifting through V2G provision. Based on the UKs current grid mix there is a dramatic increase in carbon emissions due to V2G and therefore could be considered detrimental to UK carbon reduction targets. However, as this is a projected technology and all scenarios evaluated are based upon hypothetical evaluations of future energy and EV uptake markets, future analysis indicates an environmental saving based on long run marginal emission factors.

Having evaluated the case study in great detail it is evident Manchester Science Park would benefit economically from the installation of V2G infrastructure for market and triad demand reduction. This is due to the economic benefits experienced from supplying energy through the capacity market, which is considerable even including management costs and the exceptionally high triad payments at around £35/kWh. Using this economic case, utilisation of either commuter or pool vehicles would be beneficial as the cost of installing the infrastructure is covered due to the savings experienced from supplying energy into those support scenarios.

CHAPTER SIX

SOFTWARE VERIFICATION AND VALIDATION

6.1 INTRODUCTION

This chapter provides the final development of the Vehicle-to-Grid Feasibility Analysis Environment (V2GFAE) through verification of the software to the original stakeholder specification and validation of its functionality to the user requirements (Figure 93). The process of performing verification and validation (V&V) of the software is a challenge due to the complexity of the system. Nonetheless, in order to complete the systems engineering process and confirm the effectiveness of the system created, it is important to provide a robust assessment of the software against its specification and requirements.

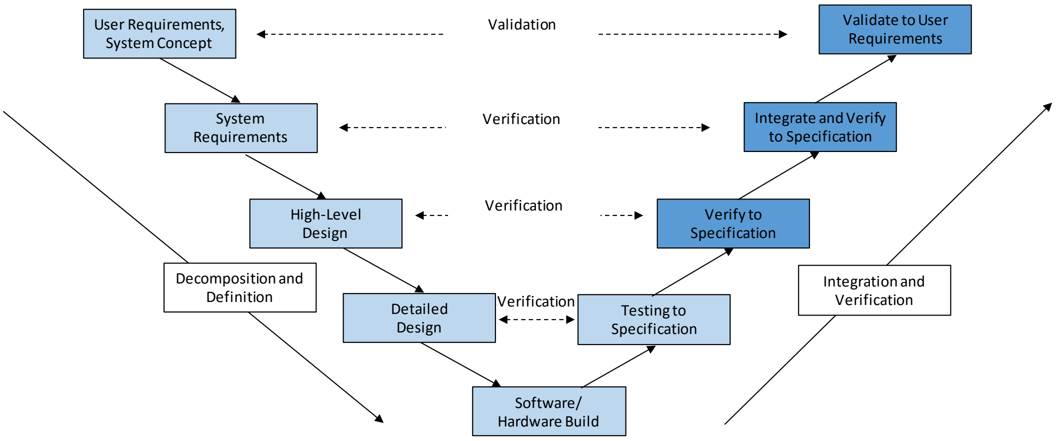


Figure 93 – Verification and Validation Phase of Systems Engineering 'Vee' Process

This chapter follows a traditional methodology for V&V, initially validating the requirements to stakeholder specifications before verification of the system design through evaluation of use cases. Finally, the functionality and build of the software is assessed, first through verification of the test cases conformance to requirements, before the whole system is validated against stakeholder requirements to confirm the correct system has been built.

6.2 METHODOLOGY

It is prudent to start with the definition of V&V in the context of software development and systems engineering. Verification is widely cited as *"are we building the product right?"* and validation, *"are we building the right product?"* [178]. In order to verify the product has been built correctly, requirements testing is performed to establish the functionality of the system. The process followed in this chapter closely follows the suggested systems engineering plan as specified by ISO/IEC/IEEE 15288. As per the recommendation made by the International Council on Systems Engineering (INCOSE), V&V has been on-going throughout the development process of the software to ensure the needs of the stakeholder are met and this is demonstrated throughout the chapter [141].

Assessment takes place over four stages, as seen in Figure 94, with the first two occupying the system design and the final two exploring the overall build of the software.

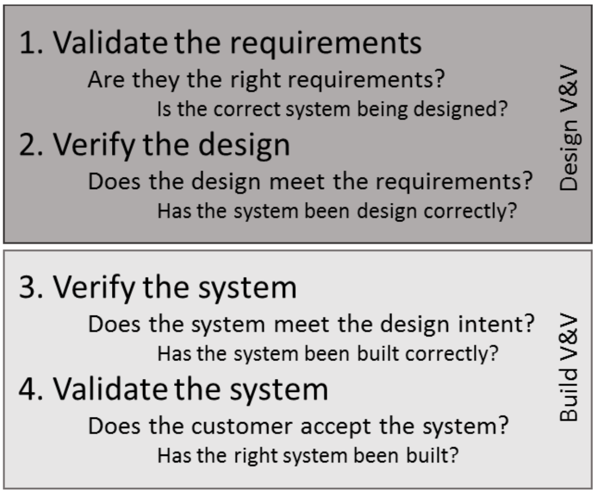


Figure 94 – System verification and validation process for design and build phases (adapted from Loughborough University Systems Verification and Validation Lecture Series)

The procedure for performing verification and validation is similar in both cases, the differences being in what the testing procedure is seeking as the outputs. The process for effective understanding and interpretation of V&V is dependent upon the understanding of the differences in verification and validation, and the efficiency and thoroughness of the processes followed. The methodology followed is outlined below as specified by INCOSE in the Systems Engineering Handbook [141]:

1. Develop the strategy for evaluation of the system through V&V.
2. Identification of the items to be verified or validated. These could be system or stakeholder requirements, system architecture (in the case of verification), the system itself or elements within or the engineering artefact (in the case of validation).
3. Identify the potential V&V constraints that could impact the implementation of actions.
4. Establish the scope of the V&V activity based upon time, monetary or other constraints.
5. Develop the testing schedule.
6. Identify and record the expected results and the success criteria.
7. Select the method or technique to be used for each item requiring verification or validation. The basic definitions of each analysis process are given by INCOSE as follows [141]:
    - ***Test*** *– method used to confirm conformance of performance or characteristics with specified requirements.*
    - ***Demonstration –*** *an activity to provide a demonstration of observable system actions.*

   - ***Inspection/ review –*** *a visual or other examination of something to demonstrate it is present.*
   - ***Analysis –*** *is the use of a model to determine or demonstrate conformance.*
   - ***Analogy –*** *the use of evidence of identical or similar systems in an identical or similar environment to confirm conformance.*
   - ***Simulation*** *– used to verify features and performance of a system as it was designed.*
   - ***Sampling*** *– a technique using samples to verify characteristics of a system.*
8. Selection of the most appropriate processes for analysis of each requirement is conducted based upon a consideration of the requirement definition and therefore the performance demonstration.
9. Identify the data needed to perform the analysis.
10. Execute the analysis and record the results.
11. Analyse the results against any expectations and success criteria to determine conformance.
12. Record any anomalies observed and performance reduction actions required.

The verification and validation plans were developed during the systems requirements and high-level design phase of the project to ensure compliance and that each system requirement is easily reviewed through the V&V process. This ensures the requirements follow the specification as defined by INCOSE as understandable, unambiguous, quantitative and testable [141].

6.2.1 SYSTEM DESIGN VERIFICATION AND VALIDATION

The procedure for verifying and validating the requirements and system design of the V2GFAE as per the process described is followed here, first for requirements validation and then verification. Information is summarised in tables to give a clear overview as to the process level being reported and the state of the item reviewed. The requirements defined in Chapter 3 (Table 12) are used for analysis in the next two sections, as per the V&V process defined by INCOSE.

6.2.1.1 REQUIREMENTS VALIDATION

In order to establish if the system has been designed with the original stakeholder specification in mind, validation of the requirements against the specification document is undertaken. This document was originally defined in Chapter 3 and has been built up using the research aims and objectives from Chapter One (Table 9). The methodology specified by INCOSE is summarised in Table 62 for the requirements validation process. This table discusses the detail of each process level to be used for the requirements validation and its associated dependencies.

Table 62 – Design validation process checklist

	Process Level	**Item**
1	Items to be validated	The items to be validated within this section are the system and stakeholder requirements, as given in Table 12.
2	Constraints	Due to the research nature of the validation schedule and the validation being at the design stage, no constraints are placed upon the process.
3	Scope	As already specified, at this stage of the analysis the scope is in validation the requirements are correct and the correct system is being designed.
4	Testing schedule	Testing follows the textual requirements specified by the stakeholders.
5	Expected results	All requirements specified by the stakeholders are presented in the requirements list, as developed in Chapter 3 and given in Table 12.
6	Success criteria	All requirements are specified and correlate to Stakeholder Project Specification Document.
7	Method for analysis	TEST T0: Inspection/ review of stakeholder text with created requirements.
8	Data required	Original specification document and developed requirements list, as per Figure 93 and Table 12.
9	Analysis results	See Table 63.
10	Conformance results	Results conform to expected outputs from analysis.
11	Anomalies/ performance reductions	None.

Evaluation of the Stakeholder Project Specification Document against the requirements defined in Table 12 is through extraction of key text from the Specification Document and identification of the related requirements. The results of this are given in Table 63, which clearly demonstrates that each of the requirements identified in the stakeholder project specification document has at least one corresponding requirement.

Table 63 – Requirements validation analysis

Requirement identified in text	**Corresponding Requirement(s)**
To evaluate the investment opportunity of V2G in a local services scenario for future energy scenarios	R1, R32
Creation of a software environment	R1, R25, R29
The investment opportunity will be assessed in terms of two key areas;	R31
a) The anticipated local economic savings	R6, R7, R8, R9, R12-R17, R27
b) The suitability of EVs with V2G to provide electricity to STOR.	R7, R11, R30
The software should be built in Matlab or Simulink to enable easy interfacing with other Matlab models within Cenex's portfolio.	R5, R28, R29, R37, R38
Specify and develop the scenarios for evaluation of the case study within the software environment.	R6, R32
Using Manchester Science Park as a case study, test the software through the built-in local services scenarios.	R4, R32
What impact does the payment tariff for EV support have on the economic suitability of EVs to provide battery storage provision?	R8, R15, R16, R19, R22, R26
What impact does the vehicle usage profile have on their ability to provide battery storage provision, both locally and for energy market trading? Two usage profiles are of primary interest; commuting and pool vehicles.	R3, R9, R10, R18, R21, R23, R24, R26, R33, R34
What is the overall suitability of electric vehicles as battery storage devices? Is one energy scenario support option more suitable than another depending upon electricity provision requirements?	R19, R36

6.2.1.2 REQUIREMENTS VERIFICATION

The method for the requirements verification procedure explores each requirement in turn and follows a test procedure to evaluate conformance of the system design to requirements based upon the MDA system design process followed in Chapter 3. The process followed during the system design process resulted in the alignment of requirements with the system design being a cyclical process. Verification of this process ensures correct design of the software before the build stage is commenced.

Table 64 – Design verification process checklist

	Process Level	**Item**
1	Items to be verified	The items to be verified within this section are the system and stakeholder requirements, as specified in Section 3 with respect to the system design.
2	Constraints	Due to the research nature of the validation schedule and the validation being at the design stage, no constraints are placed upon the process.
3	Scope	As already specified, at this stage of the analysis the scope is in verification the system design follows the requirements defined in Chapter 3.
4	Testing schedule	See Table 65.
5	Expected results	The system design matches the requirements.
6	Success criteria	System design is as specified in the requirements.
7	Method for analysis	All specified during the analysis phase after Table 65.
8	Data required	Requirements as given in Table 12and system design as given in Chapter 3.
9	Analysis results	See Table 65.
10	Conformance results	Results conform to expected outputs from analysis.
11	Anomalies/ performance reductions	None.

The process of verifying the conformance of the functional and non-functional requirements differs due to the relationship they share with the system design. Non- functional requirements are not defined in the system design phase and instead used to enable the system build. Through the MDA approach to system design used in Chapter 3, testing is relatively straight forward due to the clear methodology followed for the creation phase. A summary of the requirement number and the corresponding use case, activity or class diagram in which it is specified is given in Table 65.

Table 65 – Requirements verification analysis

Requirement	**Associated System Design Feature**	**Comments**
R1	“Create Energy Contract” Use Case	-
R2	Activity diagram for “vehicle consume energy”	-
R3	Activity diagram for “calculate energy cost”	-
R4	Activity diagram for “building consume energy”	Required for test phase (NF)
R5	Not specified within design features	Required for build phase (NF)
R6	Activity diagram for “calculate energy cost”	-
R7	Activity diagram for “create energy contract”	-
R8	Activity diagram for “calculate energy cost”	-
R9	Activity diagram for “calculate energy cost”	-
R10	Activity diagram for “vehicle transfer energy”	-
R11	Activity diagram for “calculate energy cost”	-
R12	Activity diagram for “vehicle transfer energy” and “transfer building energy”	-
R13	Activity diagram for “vehicle transfer energy” and “transfer building energy”	-
R14	Activity diagram for “vehicle transfer energy” and “transfer building energy”	-
R15	Activity diagram for “calculate energy cost”	-
R16	Activity diagram for “calculate energy cost”	-
R17	“Consume Energy” Use Case	-
R18	“Consume Energy” Use Case	-
R19	“Consume Energy” Use Case	-
R20	“Generate Energy” Use Case	-
R21	“Transfer Energy” Use Case	-
R22	“Transfer Energy” Use Case	-
R23	“Simulate Data” Use Case	-
R24	Activity diagram for “calculate energy cost”	-
R25	Activity diagram for “create energy contract”	-
R26	Not specified within design features	-
R27	Not specified within design features	-
R28	Not specified within design features	Required for build phase (NF)
R29	Not specified within design features	Required for build phase (NF)
R30	Activity diagram for “STOR Market consume energy” and “Capacity Market consume energy”	-
R31	Activity diagram for “vehicle transfer energy” and “create energy contract”	-
R32	Activity diagram for “create energy contract”	-
R33	Activity diagram for “vehicle transfer energy”	-
R34	Activity diagram for “simulate vehicle energy”	-
R35	Not specified within design features	Required for build phase (NF)
R36	Activity diagram for “create energy contract”	-
R37	Not specified within design features	Required for build phase (NF)
R38	Not specified within design features	Required for build phase (NF)

6.2.2 SYSTEM BUILD VERIFICATION AND VALIDATION

Following from the processes undertaken to verify and validate the stakeholder and system requirements of the V2GFAE, evaluation of the system build identifies firstly if the system has been built correctly and then if the correct system has been built. This is performed through first verifying the build integrity of the system before validation of the overal operation. At this stage, stakeholders will test the V2G operation to confirm performance and resulting outputs are as expected. This is performed through adding breaks into the code at each test point and reviewing the outputs from the software. This data is then reported (as shown later in the section) to inidicate if any erroneous results are presented.

6.2.2.1 BUILD VERIFICATION

Verification of the system build is performed through testing of the system against the use cases and activity diagram processes and recording the preformance of the system after running the tests. Test cases are taken from the paths demonstrated in the activity diagrams (Chapter 3 and Appendix A). They are an executable test that determine whether a system is working as intended. Each test case could have multiple evaluations performed on it to check conformance and outputs are as expected. The process follows a similar format to the requirements testing, however the test strategy is more involved due to the increased complexity of the results.

Table 66 – System build verification process checklist

	Process Level	**Item**
1	Items to be verified	The system is to be verified with respect to the requirements and expected outputs from testing.
2	Constraints	Due to the research nature of the validation schedule and the validation being at the design stage, no constraints are placed upon the process.
3	Scope	As already specified, at this stage of the analysis the scope is in verification of the system performance against the requirements.
4	Testing schedule	See Table 67.
5	Expected results	The system design matches the requirements.
6	Success criteria	System design is as specified in the requirements.
7	Method for analysis	All specified during the analysis phase, as given in Table 67.
8	Data required	Use Cases and activity diagrams are given in Appendix A.
9	Analysis results	See Table 68.
10	Conformance results	Results conform to expected outputs from analysis.
11	Anomalies/ performance reductions	None.

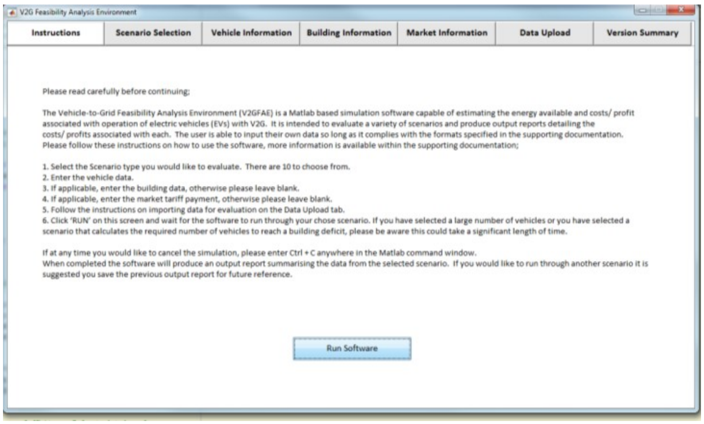
Table 67 identifies the test numbers associated with each test case, taken directly from the activity diagrams. Based on these test case allocations and the activity description the distribution of test types can then be performed, as is shown in Table 68. This table contains screenshots of the Matlab workspace to indicate where the expected output has been demonstrated.

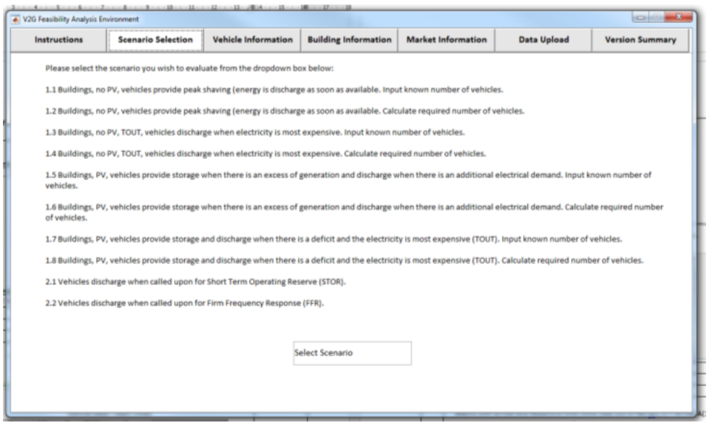
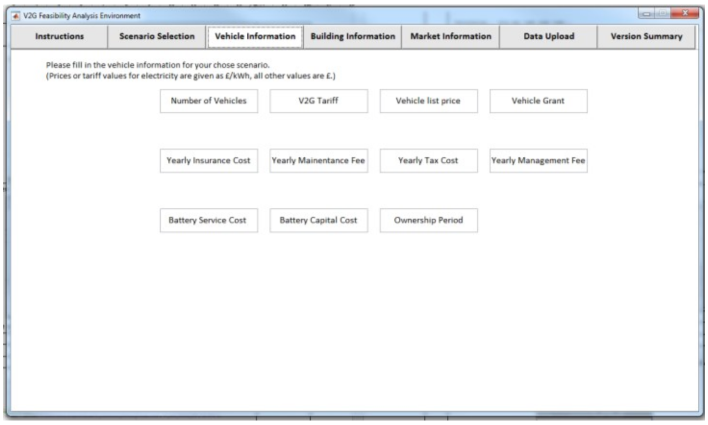
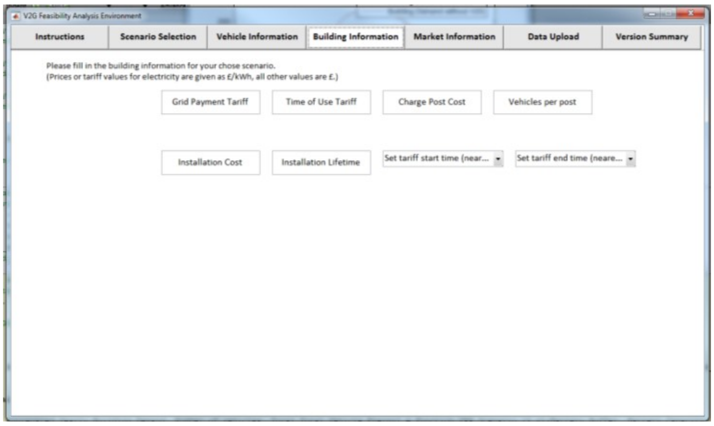
Table 67 – Build verification test schedule and analysis type

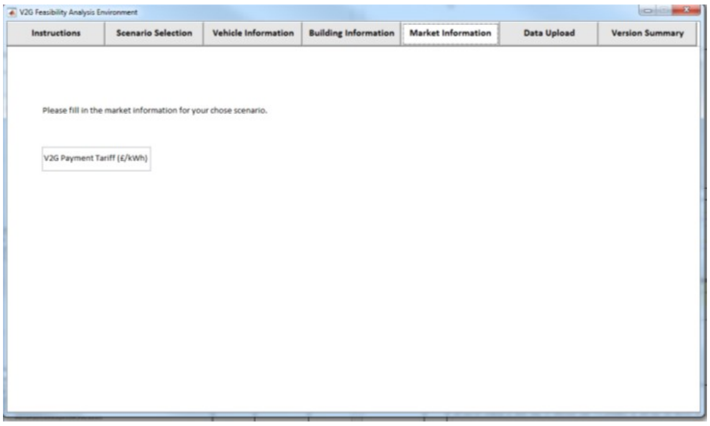
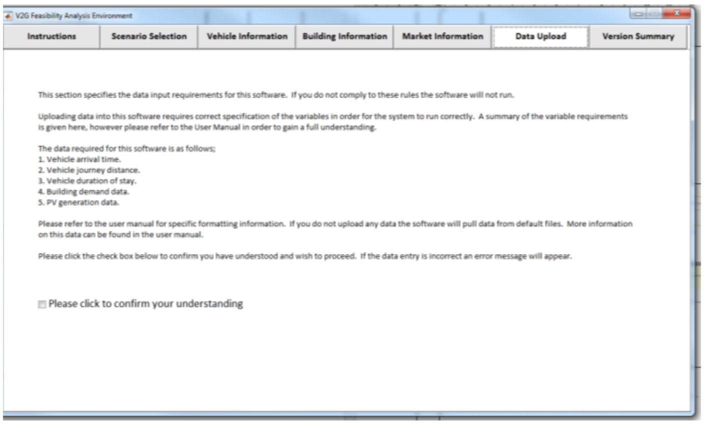
Use Case	Steps	Activity	Test	Analysis Method
Create energy contract and assess feasibility	User	Open software	T1	Demonstration
	User	Select energy scenario	T2	Demonstration
	User	Enter vehicle information	T3	Demonstration
	User	Enter building information	T4	Demonstration
	User	Enter market information	T5	Demonstration
	User	Upload data	T6	Demonstration
	User	Run software	T7	Demonstration
Simulate data	User	Import arrival time probability	T8	Test/ Inspection
	User	Import duration of stay data	T9	Test/ Inspection
	User	Import journey distance data	T10	Test/ Inspection
	Vehicle model	Simulate arrival and departure times	T11	Test/ Inspection
	Vehicle model	Calculate arrival battery state of charge	T12	Test/ Inspection
	Vehicle model	Simulate required battery departure energy level	T13	Test/ Inspection
	Vehicle model	Calculate energy available during stay	T14	Test/ Inspection
	Vehicle model	Calculate energy required for charging	T15	Test/ Inspection
Consume energy	User	Import building demand data	T16	Test/ Inspection
	Vehicle model	Calculate charging efficiency	T17	Test/ Inspection
	Vehicle model	Calculate rate of charge per time step	T18	Test/ Inspection
	Vehicle model	Add energy to vehicle battery from building	T19	Inspection
	User	Import market demand data	T20	Test/ Inspection
	User	Select analysis period	T21	Test/ Inspection
	STOR model	Simulate call out time	T22	Demonstration
	STOR model	Simulate response time	T23	Demonstration
	STOR model	Calculate start time	T24	Test/ Inspection
	STOR model	Calculate end time	T25	Test/ Inspection
	STOR model	Run vehicle model	T26	Demonstration
	STOR model	Set discharge period for vehicle	T27	Test/ Inspection
	STOR model	Stop when vehicle number reached	T28	Demonstration
	User	Import market probability data	T29	Test/ Inspection
	Capacity model	Simulate call out time	T30	Demonstration
	Capacity model	Simulate response time	T31	Demonstration
	Capacity model	Calculate start time	T32	Test/ Inspection
	Capacity model	Calculate end time	T33	Test/ Inspection
	Capacity model	Run vehicle model	T34	Demonstration
	Capacity model	Set discharge period for vehicle	T35	Test/ Inspection
	Capacity model	Stop when vehicle number reached	T36	Demonstration
Generate energy	User	Import PV generation data	T37	Demonstration
Transfer energy	Building model	Identify building requirements from scenario	T38	Demonstration
	Building model	Export/ consume PV	T39	Test/ Inspection/ Analogy

	User	EITHER specify vehicle number	T40	Test/ Inspection/ Analogy
	Building model	OR calculate required vehicle number	T41	Test/ Inspection/ Analogy
	Building model	Minus energy available within vehicle from building demand	T42	Test/ Inspection/ Analogy
	Building model	Stop when demand requirement is satisfied	T43	Demonstration
	Vehicle model	Calculate discharge efficiency	T44	Demonstration
	Vehicle model	Calculate the rate of discharge per time step	T45	Demonstration
	Vehicle model	Calculate the maximum depth of discharge	T46	Demonstration
	Vehicle model	Remove energy from vehicle	T47	Demonstration
Calculate energy cost	User	Set electricity tariffs	T48	Test/ Inspection
	User	Set infrastructure costs and lifetime	T49	Test/ Inspection
	User	Set number of days in year	T50	Test/ Inspection
	User	Set battery capital cost	T51	Test/ Inspection
	User	Set battery cycles and capacity	T52	Test/ Inspection
	Cost model	Calculate daily and yearly infrastructure costs	T53	Demonstration
	Cost model	Calculate daily and yearly building grid payment	T54	Demonstration
	Cost model	Calculate daily and yearly building vehicle payment	T55	Demonstration
	Cost model	Calculate original building grid payment	T56	Demonstration
	Cost model	Calculate required and actual vehicle income	T57	Demonstration

Table 68 – Build verification analysis output demonstrations and expected result

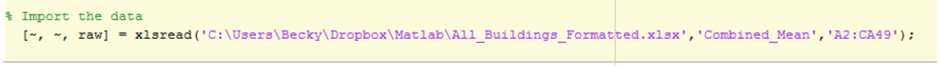
Test	**Outcome**	**Outcome expected?**
T1	Run view:  Please read carefully before continuing; The Vehicle-to-Grid Feasibility Analysis Environment (V2GFAE) is a Matlab based simulation software capable of estimating the energy available and costs/ profit associated with operation of electric vehicles (EVs) with V2G. It is intended to evaluate a variety of scenarios and produce output reports detailing the costs/ profits associated with each. The user is able to input their own data so long as it complies with the formats specified in the supporting documentation. Please follow these instructions on how to use the software, more information is available within the supporting documentation; 1. Select the Scenario type you would like to evaluate. There are 10 to choose from. 2. Enter the vehicle data. 3. If applicable, enter the building data, otherwise please leave blank. 4. If applicable, enter the market tariff payment, otherwise please leave blank. 5. Follow the instructions on importing data for evaluation on the Data Upload tab. 6. Click 'RUN' on this screen and wait for the software to run through your chose scenario. If you have selected a large number of vehicles or you have selected a scenario that calculates the required number of vehicles to reach a building deficit, please be aware this could take a significant length of time. If at any time you would like to cancel the simulation, please enter Ctrl + C anywhere in the Matlab command window. When completed the software will produce an output report summarising the data from the selected scenario. If you would like to run through another scenario it is suggested you save the previous output report for future reference.	Yes

T2	Input screen:  Please select the scenario you wish to evaluate from the dropdown box below: 1.1 Buildings, no PV, vehicles provide peak shaving (energy is discharge as soon as available. Input known number of vehicles. 1.2 Buildings, no PV, vehicles provide peak shaving (energy is discharge as soon as available. Calculate required number of vehicles. 1.3 Buildings, no PV, TOUT, vehicles discharge when electricity is most expensive. Input known number of vehicles. 1.4 Buildings, no PV, TOUT, vehicles discharge when electricity is most expensive. Calculate required number of vehicles. 1.5 Buildings, PV, vehicles provide storage when there is an excess of generation and discharge when there is an additional electrical demand. Input known number of vehicles. 1.6 Buildings, PV, vehicles provide storage when there is an excess of generation and discharge when there is an additional electrical demand. Calculate required number of vehicles. 1.7 Buildings, PV, vehicles provide storage and discharge when there is a deficit and the electricity is most expensive (TOUT). Input known number of vehicles. 1.8 Buildings, PV, vehicles provide storage and discharge when there is a deficit and the electricity is most expensive (TOUT). Calculate required number of vehicles. 2.1 Vehicles discharge when called upon for Short Term Operating Reserve (STOR). 2.2 Vehicles discharge when called upon for Firm Frequency Response (FFR). Output Format: USE_CASE in Workspace. USE_CASE 1.3000	Yes
T3	Input Screen:  Please fill in the vehicle information for your chose scenario. (Prices or tariff values for electricity are given as £/kWh, all other values are £.)	Yes
T4	Input Screen:  Please fill in the building information for your chose scenario. (Prices or tariff values for electricity are given as £/kWh, all other values are £.)	Yes

T5	Input Screen:  Please fill in the market information for your chose scenario.	Yes
T6	Input Screen:  This section specifies the data input requirements for this software. If you do not comply to these rules the software will not run. Uploading data into this software requires correct specification of the variables in order for the system to run correctly. A summary of the variable requirements is given here, however please refer to the User Manual in order to gain a full understanding. The data required for this software is as follows; 1. Vehicle arrival time. 2. Vehicle journey distance. 3. Vehicle duration of stay. 4. Building demand data. 5. PV generation data. Please refer to the user manual for specific formatting information. If you do not upload any data the software will pull data from default files. More information on this data can be found in the user manual. Please click the check box below to confirm you have understood and wish to proceed. If the data entry is incorrect an error message will appear. ☐ Please click to confirm your understanding	Yes

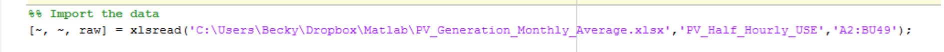
T6 (continued):

Building Demand Data:



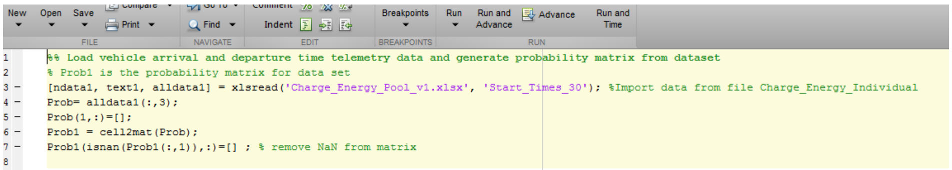
```
% Import the data
[~, ~, raw] = xlsread('C:\Users\Becky\Dropbox\Matlab\All_Buildings_Formatted.xlsx','Combined_Mean','A2:CA49');
```

PV Generation Data:



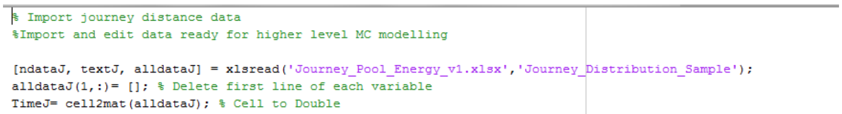
```
%% Import the data
[~, ~, raw] = xlsread('C:\Users\Becky\Dropbox\Matlab\PV_Generation_Monthly_Average.xlsx','PV_Half_Hourly_USE','A2:BU49');
```

Vehicle Data – Start Times:



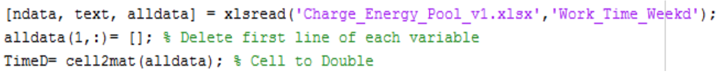
```
%% Load vehicle arrival and departure time telemetry data and generate probability matrix from dataset
% Prob1 is the probability matrix for data set
[ndata1, text1, alldata1] = xlsread('Charge_Energy_Pool_v1.xlsx', 'Start_Times_30'); %Import data from file Charge_Energy_Individual
Prob= alldata1(:,3);
Prob(1,:)=[];
Prob1 = cell2mat(Prob);
Prob1(isnan(Prob1(:,1)),:)=[] ; % remove NaN from matrix

```

Journey Distance Travelled:



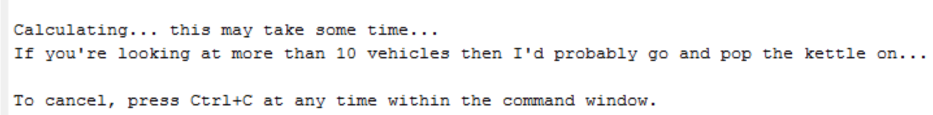
```
% Import journey distance data
%Import and edit data ready for higher level MC modelling

[ndataJ, textJ, alldataJ] = xlsread('Journey_Pool_Energy_v1.xlsx','Journey_Distribution_Sample');
alldataJ(1,:)= []; % Delete first line of each variable
TimeJ= cell2mat(alldataJ); % Cell to Double
```

Vehicle Duration of Stay:



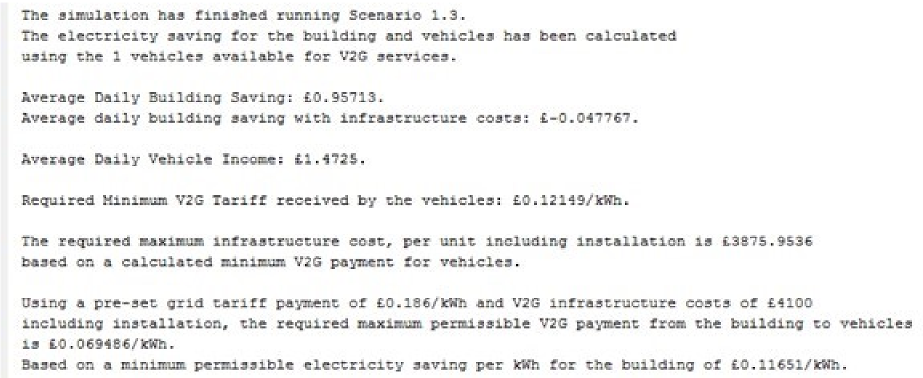
```
[ndata, text, alldata] = xlsread('Charge_Energy_Pool_v1.xlsx','Work_Time_Weekd');
alldata(1,:)= []; % Delete first line of each variable
TimeD= cell2mat(alldata); % Cell to Double
```

T7	Running Command Prompts:	Yes



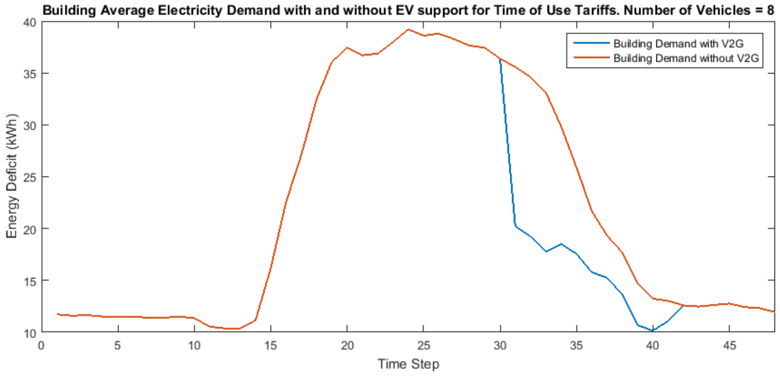
```
Calculating... this may take some time...
If you're looking at more than 10 vehicles then I'd probably go and pop the kettle on...

To cancel, press Ctrl+C at any time within the command window.
```

Completed Command Prompts:

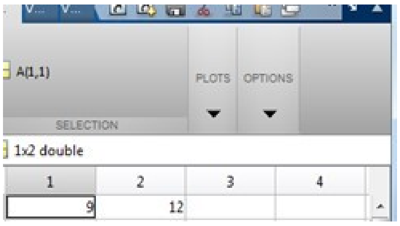


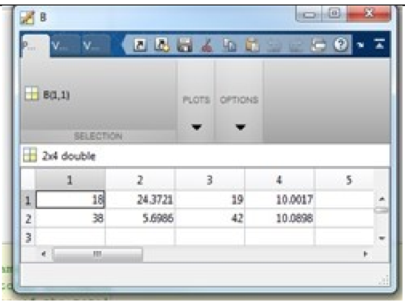
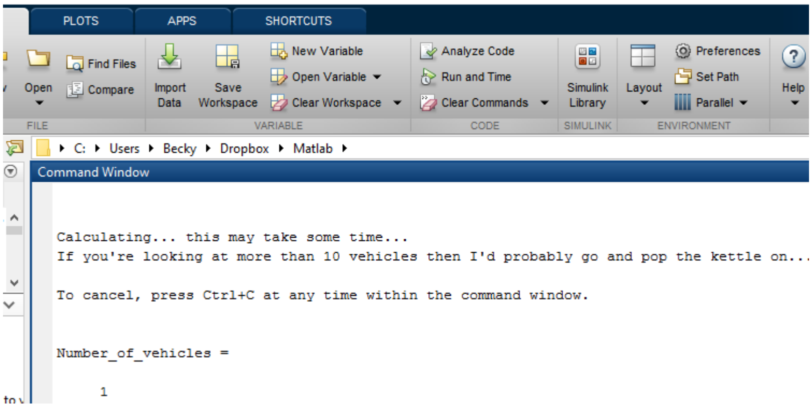
```
The simulation has finished running Scenario 1.3.
The electricity saving for the building and vehicles has been calculated
using the 1 vehicles available for V2G services.

Average Daily Building Saving: £0.95713.
Average daily building saving with infrastructure costs: £-0.047767.

Average Daily Vehicle Income: £1.4725.

Required Minimum V2G Tariff received by the vehicles: £0.12149/kWh.

The required maximum infrastructure cost, per unit including installation is £3875.9536
based on a calculated minimum V2G payment for vehicles.

Using a pre-set grid tariff payment of £0.186/kWh and V2G infrastructure costs of £4100
including installation, the required maximum permissible V2G payment from the building to vehicles
is £0.069486/kWh.
Based on a minimum permissible electricity saving per kWh for the building of £0.11651/kWh.
```

Completed Graphical Output:



Output Report: See Appendix B

T8	See T6.	Yes
T9	See T6.	Yes
T10	See T6.	Yes
T11	Output Format: Matrix with arrival and departure time (time step out of 48) A(1,1) = Arrival A(1,2) = Departure  A(1,1) 1x2 double 1 2 3 4 9 12	No – expected 2 matrices, results combine start and end time into one matrix
T12 & T13	Output Format: Matrix with arrival and departure time and battery kWh level Column 1 – Arrival Time, Column 2 – Arrival battery kWh level, Column 3 – Departure time, Column 4 – Departure battery kWh level	No – expected 2 matrices, results combine start and end time into one matrix with

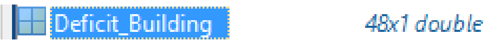
	 B B(1,1) 2x4 double 1 2 3 4 5 1 18 24.3721 19 10.0017 2 38 5.6986 42 10.0898 3	start and end kWh
T14	Output Format: Total_V2G_Energy_Supplied in Workspace.  Total_V2G_Energy_Supplied 12.6871	Yes
T15	Output Format: Total_Charge_Provision_Sum in Workspace.  Total_Charge_Provision_Sum 0.3919	Yes
T16	See T6	Yes
T17	Output Format: eta in Workspace.  eta [99.1012,96.6190]	Yes
T18	Output Format: SoC0 (initial state of charge) in Workspace.  SoC0 20 Output Format: Charge_Value_BC in Workspace.  Charge_Value_BC 48x1 double	Yes
T19	See T18.	Yes
T20	See T6.	Yes
T21	Output Format: Set_Month in Workspace.  Set_Month 1	Yes
T22	Output Format: Call_Out in Workspace.  Call_Out 41	Yes
T23	Ouput Format: Response_Time in Workspace.  Response_Time 7	Yes
T24	Output Format: Start_Time in Workspace.  Start_Time 48	Yes
T25	Output Format: End_Time in Workspace.  End_Time 10	Yes
T26	Output Format: Text in Matlab command window  C: ▸ Users ▸ Becky ▸ Dropbox ▸ Matlab ▸ Command Window	Yes

```
Calculating... this may take some time...
If you're looking at more than 10 vehicles then I'd probably go and pop the kettle on...

To cancel, press Ctrl+C at any time within the command window.


Number_of_vehicles =

     1
```

T27	Output Format: Confirm variable ‘B’ matches variable ‘Call_Duration’ in Workspace.  B [23,21.7058,27,10.6479] Call_Duration [23,27]	Yes
T28	Software is complete. Output report is published.	Yes
T29	See T6.	Yes

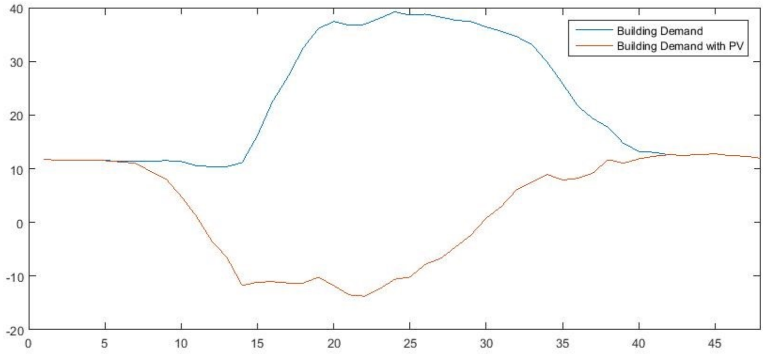
<table>
<tr><td>T30</td><td>See T22.</td><td>Yes</td></tr>
<tr><td>T31</td><td>See T23.</td><td>Yes</td></tr>
<tr><td>T32</td><td>See T24.</td><td>Yes</td></tr>
<tr><td>T33</td><td>See T25.</td><td>Yes</td></tr>
<tr><td>T34</td><td>See T26.</td><td>Yes</td></tr>
<tr><td>T35</td><td>Output Format: Capacity_Market_Duration in Workspace.

Capacity_Market_Duration 4</td><td>Yes</td></tr>
<tr><td>T36</td><td>Software is complete. Output report is published.</td><td>Yes</td></tr>
<tr><td>T37</td><td>See T6.</td><td>Yes</td></tr>
<tr><td>T38</td><td>Output Format: Deficit_Building in Workspace.



Deficit_Building 48x1 double</td><td>Yes</td></tr>
<tr><td>T39</td><td>Building demand has altered with the addition of PV generation.

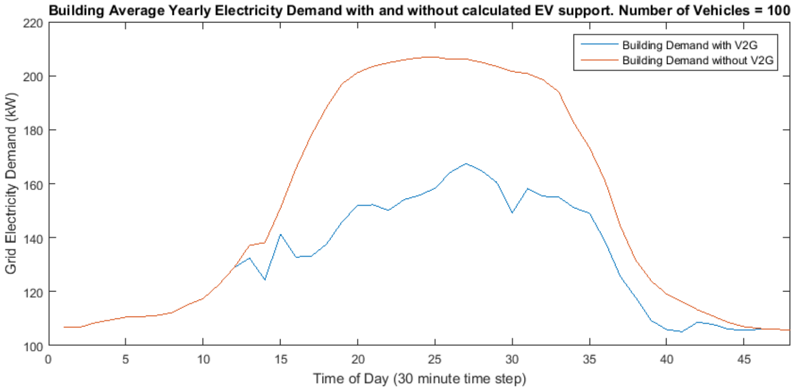
Output Format: Building_Demand_with_PV in Workspace vs. Aggregated_Yearly_Building_Demand.
Graphical comparison of demand demonstrates addition of PV.

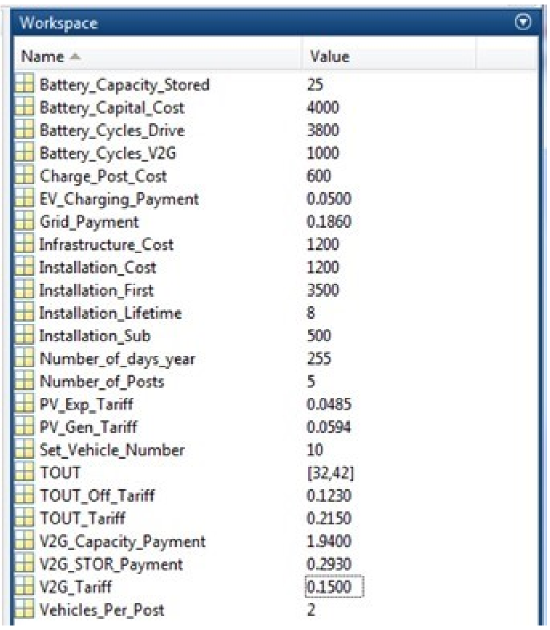

</td><td>Yes</td></tr>
<tr><td>T40</td><td>Output Format: Set_Vehicle_Number in Workspace.

Set_Vehicle_Number 5</td><td>Yes</td></tr>
<tr><td>T41</td><td>Vehicle number is displayed on output report and graphics.</td><td>Yes</td></tr>
<tr><td>T42</td><td>Building demand has altered with the addition of V2G discharge.

Output Format: Either Building_Demand_with_V2G_PV or Building_Demand_with_V2G.

Graphical comparison of demand demonstrates addition of V2G on building demand.


</td><td>Yes</td></tr>
<tr><td>T43</td><td>Software is complete. Output report is published.</td><td>Yes</td></tr>
<tr><td>T44</td><td>See T17.</td><td>Yes</td></tr>
</table>

T45	Output Format: Discharge_Value_BC in Workspace.  Discharge_Value_BC 48x1 double	Yes
T46	See T45.	Yes
T47	See T45.	Yes
T48	Output Format: Various within the Workspace.  Workspace Name Value Battery_Capacity_Stored 25 Battery_Capital_Cost 4000 Battery_Cycles_Drive 3800 Battery_Cycles_V2G 1000 Charge_Post_Cost 600 EV_Charging_Payment 0.0500 Grid_Payment 0.1860 Infrastructure_Cost 1200 Installation_Cost 1200 Installation_First 3500 Installation_Lifetime 8 Installation_Sub 500 Number_of_days_year 255 Number_of_Posts 5 PV_Exp_Tariff 0.0485 PV_Gen_Tariff 0.0594 Set_Vehicle_Number 10 TOUT [32,42] TOUT_Off_Tariff 0.1230 TOUT_Tariff 0.2150 V2G_Capacity_Payment 1.9400 V2G_STOR_Payment 0.2930 V2G_Tariff 0.1500 Vehicles_Per_Post 2	Yes
T49		Yes
T50		Yes
T51		Yes
T52		Yes
T53	See T7.	Yes
T54	See T7.	Yes
T55	See T7.	Yes
T56	See T7.	Yes
T57	See T7.	Yes

Further to the test cases presented in Table 68, 'dummy data' was run through the software that had a known pattern, where the data was created purposely with the intention of having a repetitive cycle within it. This allowed the outputs of the software to be further evaluated, as the pattern presented in the input data set must be displayed in the outputs in order for the software to be operating correctly.

Figure 95 shows the output from this testing, where a triple cycle can clearly be shown for the number of vehicles present throughout the day. This is as would be expected based on the triple cycle input data used.

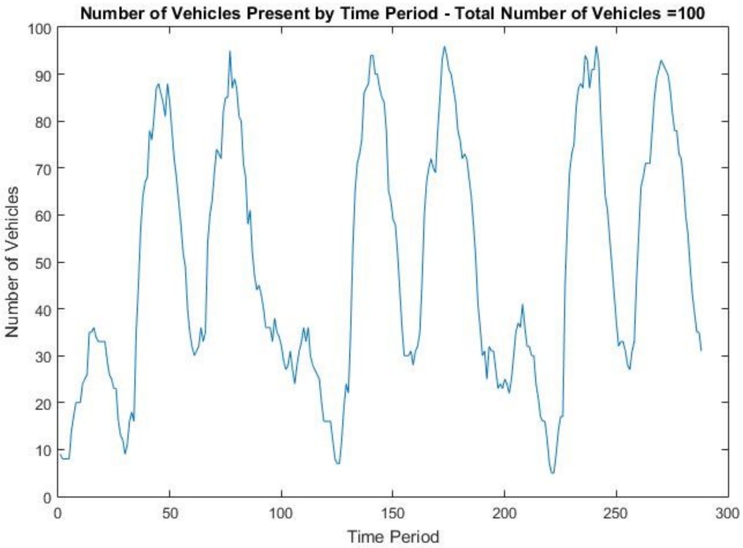


Figure 95 – Outputs from 'repetitive cycle test' for V2GFAE build verification

6.2.2.2 ERROR CORRECTION

During the software build process, a number of errors with the code were encountered that related to calculation errors, text entered incorrectly, errors with the functionality or formation of the code and errors that caused the software to end with an error code (see Table 69). These were identified through performing demonstration tests throughout the creation of the software, as have been described in Table 68. A list is displayed in Table 71 of the major errors encountered during this process. This is by no means exhaustive, but rather demonstrates the key errors that occurred and the solution chosen to fix them.

Table 69 – Error type definition

Error Type	**Description**
C	Calculation Error
T	Text Error
F	Functional Error
FF	Formation Error
P	Running Error

The removal of these errors is demonstrated in Table 71, where the expected outcomes are indicated as specified by each test case. Through performance of these test cases, compliance of the system and therefore the eradication of all known errors is proven.

6.2.2.3 BUILD VALIDATION

This requires the demonstration that the overall system has been built as per the stakeholder requirements and operates in the manner intended. This directly relates to the operational requirement specified in Chapter 3;

Develop a software environment in order to evaluate the investment opportunity of V2G in a local services scenario.

This led to the creation of an MDA view of the V2GFAE as depicted in Figure 21. Using this accepted MDA of the V2GFAE, it is anticipated the design of the system is as expected by the stakeholders. However, this can only be confirmed by the stakeholder using the software to perform analysis as intended. This was completed in two parts; first, through the case study analysis in Chapter 5; and second, through providing potential stakeholders with a 'Software Validation Questionnaire' to complete after having used the software. Evaluation of Manchester Science Park (MSP) in Chapter 5 validates the functionality of the software and the wide variety of assessment opportunities it can perform. This partially demonstrated the software fully supports the stakeholder requirements specification, given at the outset of the project, however was only supported by one system user. The questionnaire was given to Cenex employees who will be using the software to perform consultancy and research analysis on V2G scenarios. Questions were divided into three sections; 1) Software Use, 2) Software Outputs and 3) Development Suggestions and the full questionnaire is available at the end of Appendix A, along with the completed questionnaires. Overall, the speed of the software was highlighted as being slow, however it was also suggested that it saves time compared to a non-automated process. The complexity of the system was also highlighted as being both a hindrance and a help, making it more difficult to use whilst at the same time offering a multitude of assessment and analysis options which increases the usability of the software and its outputs. Overall stakeholders confirmed the information provided by the V2GFAE allows the user to form a cohesive picture of the economic viability of V2G support for buildings and energy markets.

Suggestions for further improvement are detailed as follows;

1. Providing the ability to compare multiple energy scenarios simultaneously could be beneficial as it will prevent the software user from having to re-run the software for evaluation of each scenario.
2. Could the time step be reduced from 30 minutes to maybe 5/ 10 minutes for some market based analysis?

3. The addition of static battery storage could be useful for an additional energy scenario evaluation.

These suggestions are additional to the original specification document created by the stakeholders at the outset of the project and have been provided as suggestions for further work to the V2GFAE. It is intended that these comments will be considered and built into the software at a future date.

6.2.2.4 SOFTWARE OUTPUT DATA VALIDATION

In addition to validation of the actual software, validation of the results obtained in Chapter 4 from the case study analysis is important to understand how the V2GFAE outputs compare to similar simulated or real-world results given in literature. Table 70 gives a comparison of the major results simulated in the V2GFAE vs. the closest equivalent found in the literature reviewed. Due to the software being so novel, not all results have a comparative value available.

Overall, the V2GFAE provided a more comprehensive and accurate analysis of V2G energy scenarios than comparator research. This is due to the flexibility within the software to assess multiple scenarios with an assortment of variable options. However, the comparator research relating to battery degradation costs (optimal vehicle income) from V2G services provides a greater in-depth analysis of battery degradation due to the electrochemical analysis performed in the study. Nonetheless, calculations correlate with those produced from the V2GFAE, suggesting a robust simulation process within the software.

Table 70 – Software outputs data validation comparison

Value Type	V2GFAE Simulated Result	Simulated or Real World Result
Vehicle availability	14.37% - 93.6% for all scenarios	Not comparable
Optimal vehicle income	Minimum - £0.11/kWh Maximum - £0.20/kWh	• 14.63% battery state of health reduction [179]. • £0.35/hour for ancillary service support [131].
Vehicle income	For 255 days per annum; Peak shaving – ~-£385 TOUT demand reduction – ~-£350 For 155 days per annum including infrastructure; STOR – ~-£40 Capacity market with wholesale market – ~£60	• €6 per annum for V2G [65]. • Between $170-$30 per annum for arbitrage depending upon vehicle mileage [72].
Building savings from V2G	From 50 vehicles for 255 days per annum; Peak shaving - ~£6120/annum TOUT demand reduction - ~£6556/annum Triad with TOUT demand reduction - ~£12,790	Not comparable
Optimal infrastructure price	Building related scenarios – all negative STOR – negative Capacity market - £5,450	Not comparable

6.3 CHAPTER SUMMARY

This chapter has provided the correct development of the verification and validation for the V2GFAE in accordance with standard practice. Through following a systems engineering process as exemplified by the systems engineering 'vee', analysis and testing of the software followed a regimented plan as specified in the methodology. Due to the cyclical nature of the V&V process, this chapter formed a summary of the on-going work throughout the software design, build and test phases, to ensure the suitability of the software in terms of both stakeholder requirements and performance characteristics. Initially, analysis looked to validate the requirements against the original stakeholder specification. Through comparison of the requirements specified in Table 12 with the text in the stakeholder specification document, all of the requirements were allocated to the stakeholder specification, with the exception of *R35 - User Document to describe how to use the software, all of its functionality and how to input data and the correct format for doing so.* This document is in the form of the doctoral thesis and therefore is self-evident.

Following from the clarification of requirements against initial specification, the overall system design was evaluated against its requirement counterpart. Conformance is demonstrated as all functional requirements have an associated system design feature, as followed by the MDA approach. Table 65 indicates where all non-functional requirements are exemplified through the subsequent design process, either in the form of class, activity or use case diagrams. As demonstrated, all system requirements are accounted for in the design process, indicating high conformance and therefore a thorough design of the V2GFAE is implied.

Verification of the system build uses the activity diagrams created during the MDA design process to construct test cases, from which the system build can be evaluated, as per Table 67. The outcomes are demonstrated in Table 68, where the software is either run and an output displayed, or calculations are demonstrated in sections of code from the software script. Using this method, the software is shown to perform as expected when considering the system design, however the performance of the software against the original stakeholder requirements is not so easily evaluated.

To establish the correct system has been built based on stakeholder requirements, the software must be used by the stakeholders in order to establish the overall operational requirement is met. This was conducted in Chapter 5 – Case Study Analysis, in which Manchester Science Park was used as a case study to test the real-world functionality of the software and through completion of a questionnaire by potential system users. Overall the system performed as expected, with the outputs matching those expected by the commissioning stakeholder, Cenex. The user is therefore able to accurately predict the economic viability of V2G at a given case study, for a variety of energy scenarios. Suggestions of additional operational features were given by the stakeholders after having used the software, however these are additional suggested features and the stakeholders confirmed the software runs to the original specification.

The overall process of V&V therefore not only confirms the design and built integrity of the system under evaluation, but enables the system evaluator to establish the constraints and benefits of the system. This extends to demonstration of errors within the system, created during the build phase of the system life-cycle process. It is suggested that without following this testing and evaluation process, those errors may not have been discovered. Therefore, the cyclical nature of software build followed throughout this thesis, culminating in the V&V of the software demonstrates the robust nature of the software created.

Table 71 – Identified and resolved errors within the V2GFAE

	Error Type	Error Description	Location of Error	Output with Error	Resolution
E1	C	Vehicle arrival information taken from incorrect distribution curve	MAINSCRIPT_AD_Times_REAL_DATA_30MINS_v4	Information calculated incorrect	Re-wrote loop to consider the correct distribution curve from which to sample
E2	C.P	Arrival probability table incorrect size	MAINSCRIPT_AD_Times_REAL_DATA_30MINS_v4	Error message, software will not perform	Added re-sizing code to remove NaN from imported excel file
E3	C	Vehicle departure times could be calculated after the 24 hour period	MAINSCRIPT_AD_Times_REAL_DATA_30MINS_v4	Will produce infinate energy transfer values	Added loop to replace departure times after 24 hours with maximum daily value
E4	F	Extra zeros in arrival and departure matrix	MAINSCRIPT_AD_Times_REAL_DATA_30MINS_v4	Produces incorrect departure/ arrival information	Added code to delete '0' values
E5	T.P	Calling from incorrect script file for arrival energy consumption script	MAINSCRIPT_SoC_Arrival_REAL_DATA_30MINS_v2	Sampled from an earlier version of the file in which the time step was smaller. Software would not run.	Re-wrote the script file name
E6	C	Vehicle arrival information taken from incorrect distribution curve	MAINSCRIPT_SoC_Arrival_REAL_DATA_30MINS_v2	Information calculated incorrect	Re-wrote loop to consider the correct distribution curve from which to sample
E7	C	Battery energy level calculated incorrectly	MAINSCRIPT_SoC_A_D_WORKING_V1	Incorrect information relating to energy available within EV battery	Re-wrote equation
E8	C.P.F	Battery discharging incorrectly	All discharge functions	Vehicles continue to discharge after building demand is met	Added script to stop simulation when demand is met
E9	C.P.F	Battery discharging incorrectly	All discharge functions	Vehicles discharge to infinate value	Code written to block this performance error
E10	C.P.F	Battery discharging incorrectly	All discharge functions	One vehicle charging and discharge at the same time	Code written to remove discharge if there is a charging requirement
E11	C.P.F	Battery charging incorrectly	All charge functions	Vehicles charging in PV model when there is no excess PV generation	Code written to block charging in the event building demand = 0kW
E12	C	Time of use tariff calculations incorrect	Function_TOUT_v1	TOUT calculation incorrect. Not producing desired output	Calculations re-written correctly
E13	FF	Cannot specify the vehicle support number	All scenario functions	Could select the number of runs but not the number of vehicles, which could be less if some vehicles simulated are unsuitable for the scenario	Code written to re-run the simulation each time an unsuitable vehicle is run
E14	C	Cost of charging vehicles not included in cost calculations	All cost model scripts	Income required by vehicles was falsly low	Added in line of calculations to account for this

CHAPTER SEVEN

CONCLUSIONS AND EVALUATION

7.1 CONCLUSIONS

The diversification of the UK energy supply chain from large fossil fuel power plants to an assorted collection of traditional, renewable and nuclear generation, as well as increasing storage provision demonstrates a changing energy supply chain [5]. Energy demand is also changing, both in type and location, with an ever increasing population and migration of population to large towns and cities [9]. Electric vehicles (EVs) will represent a huge additional draw on the electricity network in future years, with up to 60% of new car sales expected by 2030 [14]. Methods of utilising this additional demand as not only an energy draw but as an energy store is of great interest. Much research has already been conducted to evaluate the potential of EVs in providing energy storage provision to local buildings and wider energy markets. Of key interest is the economic potential for EVs with V2G in a variety of scenarios in the UK. A platform from which this can be evaluated was identified as being beneficial, enabling industry to gain an understanding of the relationships between key elements of the system including users, batteries, building, energy transfer and market demand. The aim of this research project was therefore to create a platform from which to evaluate the investment opportunity of vehicle-to-grid (V2G) in a local services case study for future energy scenarios.

This platform, the Vehicle-to-Grid Feasibility Analysis Environment (V2GFAE) takes data from actors such as buildings, vehicles and energy markets to evaluate the investment opportunity of V2G in a local services context. The output of this software platform is to provide information regarding the economic viability of the case study data within the energy scenario it has been evaluated through. Six energy scenarios exist within the software for EV battery utilisation for both building demand reduction and market support. These include both specifying and calculating the required number of EVs for building support and run through support options such as peak shaving, tariff support, load shifting using PV, short term operating reserve (STOR) and capacity market support with wholesale market trading.

Evaluation of the case study, Manchester Science Park (MSP), through the V2GFAE identified the capacity market with half-hour day-ahead wholesale market trading as holding the greatest investment opportunity for V2G. This scenario had a simulated net present value of over £420,000 including the infrastructure costs after 10 years of operation using 50 vehicles for 1 hour a day, 3 days a week. The other energy scenarios used to evaluate the case study were found not to be promising investment opportunities due to the cost of infrastructure and degradation effects of the vehicle battery from V2G provision.

The following sections summarise the main conclusions from the research conducted, along with indicating where the main research objectives have been satisfied.

7.1.1 DEVELOPMENT OF A MODEL DRIVEN ARCHITECTURE FOR THE V2GFAE

Using a model driven architecture (MDA) methodology the system requirements were developed, from which the subsequent software was created. Through clarification of the structure and location of the software using an MDA approach the structure and performance requirements of the software were refined and developed to form a robust requirements list. The overall formation progressed from a linear modulation approach into a bottom up system, with each of the actors representing a different sub-model (or individual system within the system-of-systems). The use cases were used as the basis of the system architecture specification and form the foundation for the software creation in Chapter 4. These were; "calculate energy cost", "simulate data", "generate energy", "consume energy" and "transfer energy". This requirements process was also invaluable during the verification and validation procedure, enabling thorough and robust evaluation, which confirmed the success and functionality of the V2GFAE against the original stakeholder requirements specification.

7.1.2 VEHICLE-TO-GRID SUPPORT SCENARIO OPTIONS

Six energy scenarios were identified during the system design process as most beneficial for analysis within the software. Four of these explore EV and building support opportunities and two consider energy market opportunities. The four building scenarios are; peak-shaving, tariff-shaving, peak-shaving with PV charging and tariff-shaving with PV charging. Market scenarios are; short term operating reserve (STOR) and the capacity market with wholesale electricity market trading. The building scenarios allow the software user to either calculate the number of vehicles required to offset the building's grid electricity demand, or input the required number of vehicles to provide full building support. The capacity market scenario also allows the software user to either specify or calculate EV requirements based upon the specified energy provision requirement. Scenarios explore simple discharging of vehicles, discharging batteries during tariff times and charging during periods of excess PV generation. Through development of these evaluation scenarios, software users are able to amass a comprehensive understanding of the opportunities available to EVs in relation to V2G. The software provides a platform for users to establish the most suitable support strategy for the vehicle usage profiles being evaluated and provide specific demand and generation information for the buildings and PV.

7.1.3 CREATION OF A STOCHASTIC BASED APPROACH TO VEHICLE USAGE MODELLING

Representative vehicle usage patterns were generated using a stochastic, Monte Carlo based simulation. Using a transition probability matrix, vehicle data relating to destination arrival time was sampled from to generate the probability of arrival in a particular time period (nominally 30 minutes). This is a novel way of generating vehicle journey information and through implementing it into the V2GFAE, any data set can be used. This vehicle model forms the basis for the rest of the software to be built, connecting to the building and market sub-models and then onto the cost sub-models for economic analysis. An additional property of this modelling approach meant the uncertainty of the data output from the software could be easily compared to that of the original dataset. The sensitivity analysis performed indicated the data was within 3 standard deviations from the mean, and the tornado plots demonstrating an agreement with the variation in results expected.

7.1.4 VEHICLE-TO-GRID COST EVALUATION OPPORTUNITIES

The true value of the software is in the opportunity to evaluate the success of the selected energy scenario on an economic basis. The cost sub-models are directly related to the scenario being evaluated, with building savings and vehicle income calculated. The vehicle cost sub-model was found to be effective in establishing the benefit of each scenario to the vehicle, with some vehicle use profiles providing negative payments due to the energy demand requirements from the scenario selected. A useful element of the cost evaluation conducted through the V2GFAE software is in establishing optimum infrastructure costs to satisfy the payment requirements set by the vehicles and the existing electricity tariffs paid by the building. The same can be said for the vehicle optimisation cost sub-model, through which the minimum price per kWh of electricity can be calculated based upon the vehicle usage profile, demand and battery degradation. Development of these cost calculations proved invaluable in developing a complex understanding of the economics relating to buildings, the STOR and capacity energy markets and EVs.

7.1.5 INPUT DATA EVALUATION

The data used for the case study analysis and subsequent verification and validation (V&V) of the V2GFAE was assessed with regards to its quality and integrity. Several large data sets were used to perform testing and V&V of the software relating to building demand, PV generation, vehicle usage and market demand. Initially a case study description was explored, evaluating the type and general usage of the buildings under evaluation at MSP. This highlighted the diversity of the buildings under review, with all six having a combination of office spaces combined with more intense energy usage spaces such as data labs, research facilities and lab spaces. Overall, the building demand data had expected variation due to seasonal impacts, with the robustness of the data collection strategy employed at MSP benefiting the overall data collection for the case study analysis. The PV data was based on PVSyst generated data and relates to each of the six buildings specific roof size and orientation.

The vehicle usage data was collected from a field trial of nearly 350 EVs over a 1.5-year period. Data was separated by usage type (pool/ commercial or commuter) and by journey and charging data. The telemetry data from a number of these vehicles provided skewed readings, leaving data from 66 of the vehicles suitable for analysis; 13 commuter and 63 pool vehicles. The spread of data for both commuter and pool vehicles was broad, with distance travelled per journey having a standard deviation of 8.57 and 5.39 for commuter and pool vehicles respectively. This highlighted the benefit a Monte Carlo based modelling approach would have on overall output results, with data variance improving after input into the V2GFAE.

Finally, assessment of the market demand data for STOR and the capacity market with additional wholesale market trading was undertaken within the V2GFAE to assess the potential call out periods for both markets. Price data was specified on a month-by-month basis, with STOR having both availability and utilisation payments associated to each of the vehicles. The capacity market income relates to the closeout price for the capacity market, paid to the VPP as a management fee and for the installation of infrastructure. Payments made to the vehicles are calculated from the half-hour day-ahead wholesale electricity market and are based on average seasonal prices.

7.1.6 VEHICLE USAGE PROFILES AND THEIR IMPACT ON VEHICLE-TO-GRID ECONOMICS

An evaluation of commuter and pool vehicles was undertaken to establish which profiles were more suitable for support scenarios than others in terms of economic viability at MSP. In running the software through every scenario with 75 vehicles selected for each, a comparison as to the percentage of vehicles available for the scenario was possible. The evaluation showed scenario B4 to be the most suitable for the commuter vehicles, with 94% of the vehicles available. This was likely due to the charging requirement imposed upon the vehicles, with the majority of vehicles available for charging at some point during the day. The pool vehicles demonstrated a converse result, with scenario B1 proving the best in terms of vehicle availability, with 72% of the vehicles available. This is due to the usage patterns of the pool vehicles being more sporadic throughout the day, with vehicles being utilised for short journeys at any point throughout the day. The STOR and capacity market support scenarios were the least supported, with just 16% and 14.37% of pool vehicles available for STOR and capacity market respectively. It is suggested however, that through economic incentives to commuters it is likely this value could be increased.

7.1.7 VEHICLE-TO-GRID TARIFF STRUCTURES AND PRICING

An evaluation of a variety of tariff types for commercial buildings was performed, demonstrating the impact of tariff pricing, electricity demand patterns and vehicle usage profiles on the suitability of vehicles for specific support options. The required income generated for the vehicles was proportional to a number of variables including battery cost, number of V2G cycles and depth of discharge. Overall, those scenarios where a greater depth of discharge was achieved per battery cycle had a lower cost per kWh of electricity transferred. This is due to a greater overall income generated from the scenario. Utilisation of the vehicles for support of the aggregated MSP therefore yielded a more positive result than for the individual Enterprise Building due to a much higher energy provision value. This correlated with the building income generated, with significantly more cost savings achieved for the aggregated building demand than for the Enterprise Building alone. This was largely due to a lower number of vehicles required for support. Of key interest was the impact of reducing the building demand in order to reduce the triad charges associated with the building. Based on the analysis performed using the V2GFAE, is was estimated savings could be as much as £14,250 per annum with 30 vehicles performing V2G services.

Variation of the electricity tariffs including V2G payment from the building to the vehicle, grid demand payment, and peak and off-peak triad costs was also performed. Results demonstrated the sensitivities surrounding these values, with the grid electricity prices offering the greatest flexibility in terms of savings generated. It is predicated that due to increasing grid electricity prices long term the economic savings to both the building and vehicles will increase as time goes on.

7.1.8 THE IMPACT OF VEHICLE-TO-GRID INFRASTRUCTURE PRICING

Infrastructure pricing proved to be the most influential in terms of impact of the economic viability of the scenarios evaluated. For both the aggregated MSP demand and Enterprise Building the income generated was not sufficient to cover the cost of the infrastructure. It is therefore suggested only scenarios in which infrastructure is required for vehicle charging in addition to the provision of V2G services are suitable. In the case of MSP, this would be for pool vehicle charging.

However, if MSP continue with their triad payment scheme, payback could be achieved within 7 years of installation. The cost for infrastructure was based upon the calculated costs to match vehicle V2G payments and the costs derived from current charging infrastructure pricing. However, this is not realistic in terms of the current V2G infrastructure market, with systems available costing in the region of £30,000 including installation. Through projection analysis based upon a PV cost reduction model it is anticipated the cost of the infrastructure will match that of current UK charging posts within 5-6 years. This aligns with projected future uptake and therefore further confirms the economic potential of the technology.

7.1.9 VERIFICATION AND VALIDATION OF SOFTWARE

V&V was performed on the software following a traditional systems engineering approach, where initially the requirements were validated and system design verified to complete the system design V&V. This was followed by the system build V&V, where the system was verified before being validated against the original stakeholder requirements specification. This was performed by the assessment of MSP as the case study in Chapter 5, all other V&V was completed in Chapter 6. The test strategy followed was specified by the INCOSE Systems Engineering Handbook [141] and ensured a robust assessment of the software design and build. Through this process an analysis method was created and expected outcomes evaluated, with every test providing 'as expected' results except for two, where additional steps were added to provide a more complex software output. In addition, an error specification was created in order to record key errors within the system during the build phase. 14 key errors were identified, all fixed during the build phase, demonstrating the effectiveness of the cyclical system engineering process followed. Finally, results from the V2GFAE were validated against values obtained from other research in the field which proved difficult due to the novelty of the research.

7.1.10 CARBON OFFSETTING FROM VEHICLE-TO-GRID IMPLEMENTATION

Finally, additional analysis conducted evaluates the impact increased EV battery cycling and energy utilisation could have on the environment. Analysis evaluated two exemplar case studies, one base case providing daytime charging at MSP and the second providing charging at night and PV load shifting during the day through V2G services. Due to the additional charging requirements placed upon the vehicle and therefore increased generation output from the grid, carbon emissions actually increased for short-run emissions testing. However, based on a projected marginal emissions factor for long run, emissions could be reduced to zero within 10 years, further demonstrating the suitability of this technology in a future energy scenario.

7.2 RECOMMENDATIONS FOR FUTURE WORK

During the process of creating this research thesis, several opportunities for further research were identified that lay outside the scope of the original work. Nonetheless, they would be interesting to explore further at a later stage and are detailed as follows:

1. Whilst the V2GFAE software rigorously evaluates six energy scenarios, it is acknowledged there are many more that could have been considered. The energy market analysis evaluates only STOR and the capacity market as a potential market for V2G utilisation. It is therefore suggested further work could be to explore the wider energy markets available to EVs with V2G.
2. The V2GFAE only simulates data for one 24-hour period. The data input into the software specifies the average day from which the data is sampled from (for example, only importing data from June will provide simulated results based upon an average day in June). It would be useful to add functionality to enable the user to select the duration of time they wish to evaluate, for example month, day or year.
3. The only battery storage device currently evaluated is EVs. It would be beneficial to expand the scope of the software to include static battery storage devices, as well as additional renewable generation technologies such as combined heat and power (CHP).
4. Development of a more sophisticated discharging and charging strategy within the vehicle model may be beneficial. Through development of some control algorithms the vehicle management could become more realistic on an individual vehicle basis. However, upon aggregation of multiple vehicles the outcome shows little difference at a simulation scale.
5. Currently the software simulates only one scenario at a time. The user is expected to save the outputs from the simulation and re-run the software to evaluate a different scenario. Providing the user with the opportunity to perform simultaneous scenario analysis would improve the efficiency of the V2GFAE software.
6. A brief exploration of the environmental impacts of V2G was undertaken. However, there could be benefit in integrating a more sophisticated evaluation strategy into the V2GFAE.
7. Finally, the total cost of ownership (TCO) of EVs with V2G in comparison with traditional internal combustion engine vehicles or EVs without V2G provision could be of benefit. This was identified as not being novel due to a number of TCO models currently in existence, however a knowledge of the impact V2G has on EV TCO would nonetheless be interesting to explore.

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APPENDIX A

SYSTEM ARCHITECTURE

A1. SIMULATE DATA

Use Case Name: Simulate Data

Brief Description:
This use case describes the process by which the software simulates vehicle consumption and journey information in order to establish battery energy levels and availability.

Goal:
Correctly simulated vehicle arrival and departure time and battery energy level.

Success Measure:

1. System produces matrix containing arrival time, arrival SoC and departure time, departure SoC.
2. System produces matrix with RoC and RoD per time step.

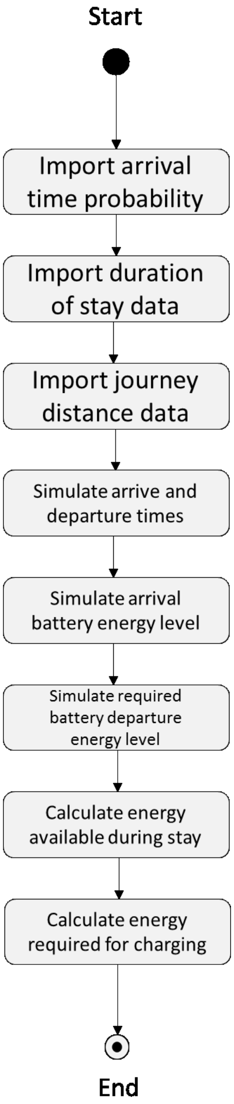
Pre-conditions:

- System is operational
- Vehicle data is available for case study analysis required. This includes time of arrival, journey distance and duration of stay data.

Typical Flow of Events (Vehicle):

- Import vehicle arrival time probability.
- Import vehicle duration of stay data.
- Import vehicle journey distance travelled data.
- Simulate vehicle arrival and departure time.
- Simulate vehicle arrival battery energy level.
- Simulate required departure battery energy level.
- Calculate energy available during stay.
- Calculate energy required for charging.

A1.1 ACTIVITY DIAGRAM FOR USE CASE "SIMULATE DATA"



A1.1.1 DESCRIPTION FOR ACTIVITY DIAGRAM “VEHICLE SIMULATE DATA”

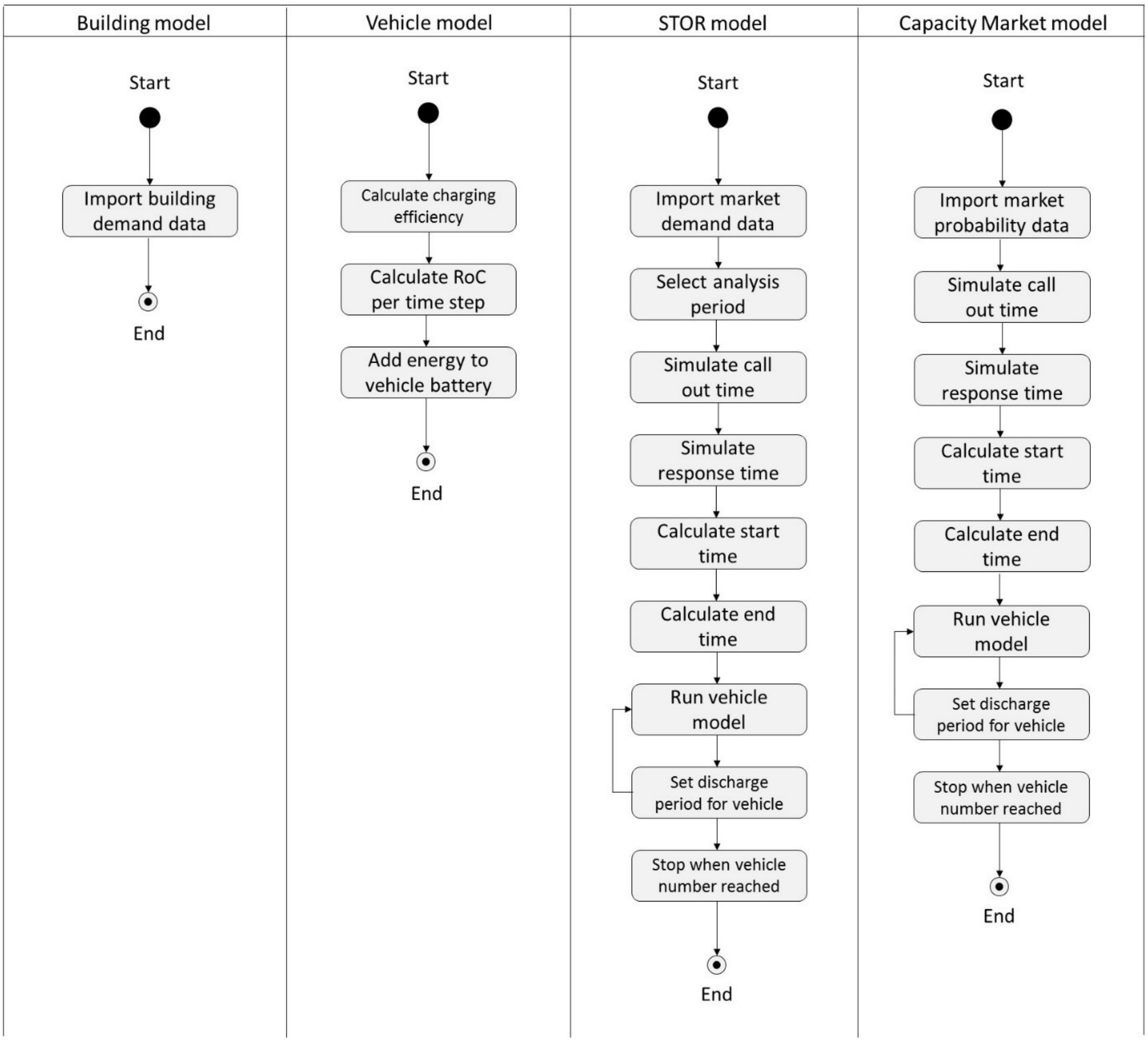
	Activity	Description
1	Import vehicle arrival time probability	**Output Format:** Probability of vehicle arriving per ½ hour time step
		Process: 1. Round times in data to nearest ½ hour. 2. Calculate number of arrivals per time step. 3. Calculate probability of arrival.
2	Import duration of stay data	**Output Format:** Stem and leaf diagram of arrival time vs. duration of stay
3	Import journey distance data	**Output Format:** stem and leaf diagram of arrival time vs. distance travelled
4	Simulate vehicle arrival and departure times	**Output Format:** Produce two matrix – 1) arrival times (time step) and 2) departure time (time step)
		Process: 1. Generate 48 random numbers between 0 and 1, assign as ‘x’ with probability function. 2. Compare to probability of arrival using transition probability matrix. 3. Generate normal distribution for vehicle ‘duration of stay’ for each time period using mean and standard deviation; $mean(\mu) = \frac{\sum x}{n}$ where; x is the observed value and n is the number of values in the set and the standard deviation is; $\sigma^2 = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}}$. This produces a normal distribution with probability density function; $P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma^2)}$ [154] 4. Calculate which distribution to sample from based on arrival time. 5. Calculate end time. 6. If end time ≥ 48, STOP 7. LOOP back to 1. until Departure time ≥ 48, then STOP.
5	Simulate vehicle arrival battery energy level	**Output Format:** Produce matrix with battery energy value (kWh) vs. time step
		Process: 1. Set maximum battery capacity. 2. Set vehicle Artemis values. 3. Create normal distribution from vehicle journey distance for each hour as per step 4.3. 4. Calculate which distribution to sample from based upon arrival time as per step 4.4. 5. Loop until all arrival times have a corresponding journey distance. 6. Calculate drive cycle efficiency for each journey using either an average, urban, road or motorway Artemis value. 7. Calculate arrival battery energy value. 8. Calculate arrival state of charge (SoC).
6	Simulate required departure battery energy level	**Output Format:** Produce matrix with battery energy value (kWh) vs. time step
		Process: 1. 3. Create normal distribution from vehicle journey distance for each hour as per step 4.3. 4. Calculate which distribution to sample from based upon arrival time as per step 4.4. 5. Loop until all arrival times have a corresponding journey distance. 6. Set battery buffer (percentage battery capacity cannot drop below).

		7. Calculate drive cycle efficiency for departure journey as per step 5.6. 8. Calculate departure battery capacity. 9. Calculate departure state of charge (SoC).
7	Calculate energy available between arrival and departure	**Output Format:** Produce value per arrival and departure
		Process: 1. Calculate energy difference between arrival and departure. 2. Loop for each arrival time.
8	Calculate energy required for charging	**Output Format:** Value of energy input to battery for charging
		Process: 1. Calculate energy difference between maximum energy level and arrival energy level. 2. Loop for each arrival time.

A2. CONSUME ENERGY

Use Case Name: Consume Energy
Brief Description: This use case describes the process by which the software simulates energy consumption for the building, vehicle and energy market models.
Goal: Building - Demand data is imported; Vehicle – energy level increases; Energy market – calculate demand time.
Success Measure: Building – demand matrix is populated; Vehicle – energy level has increased (matrix); energy market – demand matrix is populated with demand requirement period.
Pre-conditions: • System is operational. • Demand data is available for case study analysis required. • Vehicle data has been simulated.
Typical Flow of Events (Building): • Import building demand data.
Typical Flow of Events (Vehicle): • Charging efficiency us calculated. • The rate of charge is calculated per time step. • Energy is added to vehicle.
Typical Flow of Events (STOR Market): • Import market demand data. • Select analysis period. • Simulate call out duration. • Simulate response time. • Calculate start time. • Calculate end time. • Run vehicle model. • Set discharge period for vehicle. • Stop when vehicle number is reached.
Typical Flow of Events (Capacity Market): • Import market probability data. • Simulate callout time. • Simulate response time. • Calculate start time. • Calculate end time. • Run vehicle model. • Set discharge period for vehicle. • Stop when vehicle number is reached.

A2.1 ACTIVITY DIAGRAM FOR USE CASE "CONSUME ENERGY"



A2.1.1 DESCRIPTION FOR ACTIVITY DIAGRAM "BUILDING CONSUME ENERGY"

	Activity	Description
1	Import building demand data	**Output Format:** Date vs. ½ hour for kWh demand

A2.1.2 DESCRIPTION FOR ACTIVITY DIAGRAM “VEHICLE CONSUME ENERGY”

	Activity	Description
1	Calculate charge efficiency	**Output Format:** Percentage (%)
		Process: 1. Calculate charge (or discharge) efficiency per ½ hour time step. $$\eta = \frac{OCV - V}{OCV}$$ Where η is charge efficiency, OCV is open-circuit voltage and V is voltage. 2. Calculate new state of charge (SoC) per half-hour time step $$SoC(t) = SoC(0) - \frac{1}{C_{bat}} \int I.dt$$
2	Calculate RoC per time step	**Output Format:** KWh value per time step
		Process: 1. Calculate total time available. 2. Calculate total storage capacity available. 3. Calculate the charge value (Charge_Value_BC). 4. Calculate new battery energy level (kWh).
3	Add energy to vehicle battery	**Output Format:** Matrix with vehicle energy level per time step.

A2.1.3 DESCRIPTION FOR ACTIVITY DIAGRAM “STOR MARKET CONSUME ENERGY”

<table>
<tr><th></th><th>Activity</th><th>Description</th></tr>
<tr><td>1</td><td>Import market demand data</td><td>Output Format: Time of year vs. time periods of peak call demand</td></tr>
<tr><td>2</td><td>Select analysis period</td><td>Output Format: Number from 1-6 as specified.</td></tr>
<tr><td></td><td></td><td>Process:
Set the month to subsequently set the window time.
1: April
2: May-August
3: September
4: October
5: November - January
6: February - March</td></tr>
<tr><td>3</td><td>Simulate call out time</td><td>Output Format: Random number (whole integer between 1 and 48 inclusive).</td></tr>
<tr><td></td><td></td><td>Process:
1. Specify the time periods for potential call out times based upon analysis period selected.
<table>
<tr><th>Month</th><th>Windows</th></tr>
<tr><td>April</td><td>07:30 – 14:00 and 19.30 – 22.30</td></tr>
<tr><td>May-August</td><td>00:30 – 14:30, 16:30 – 18:30 and 20:00 – 23:00</td></tr>
<tr><td>September</td><td>08:00 – 14:30 and 16:30 – 22:00</td></tr>
<tr><td>October</td><td>08:00 – 14:00 and 16:00 – 21:30</td></tr>
<tr><td>November-January</td><td>07:30 – 14:00 and 16:30 – 21:30</td></tr>
<tr><td>February-March</td><td>08:00 – 14:00 and 17:00 – 21:30</td></tr>
</table></td></tr>
</table>

		2. Generate a random integer between 1 and 48 inclusive. 3. Create ‘if’ statement to establish compliance of random number with window specified. Else, re-start.
4	Simulate response time	**Output Format:** Random number (whole integer between 1 and 4 inclusive).
5	Calculate start time	**Output Format:** Single integer value (between 1 and 48 inclusive).
		Process: 1. Calculate start time.
6	Calculate end time	**Output Format:** Single integer value (between 1 and 48 inclusive).
		Process: 1. Calculate end time. 2. Put start and end time into matrix with the following format: Start_End_Time = [xx,xx]
7	Run vehicle model	See ‘Vehicle Transfer Energy’
8	Set discharge period for vehicle	**Output Format:** Function to replace vehicle availability with STOR discharge requirement values.
		Process: 1. Create if loop to replace vehicle arrival time with STOR discharge start time if it satisfies certain conditions. 2. Create if loop to replace vehicle departure time with STOR discharge start time if it satisfies certain conditions.
9	Stop when vehicle number is reached	**Output Format:** Simulation ends and runs into cost model

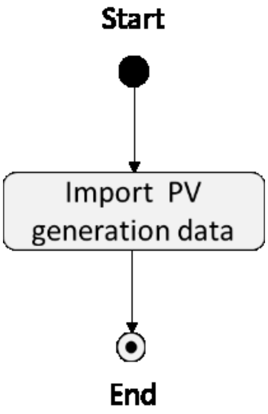
A2.1.4 Description for activity diagram “Capacity Market consume energy”

	Activity	Description
1	Import market probability data	**Output Format:** probability of start time vs. time step
3	Simulate call out time	**Output Format:** Random number (whole integer between 1 and 48 inclusive).
		Process: 1. Generate 48 random numbers to simulate start time – ‘x’. 2. Compare ‘x’ to probability. N(t) = 1 if x(t) ≤ Probability(t). 3. When N(t) = 1, stop simulation and assign value of (t) as start time. 4. Set discharge duration. 5. Calculate end time.
4	Simulate response time	**Output Format:** Random number (whole integer between 1 and 4 inclusive).
5	Calculate start time	**Output Format:** Single integer value (between 1 and 48 inclusive).
		Process: 1. Calculate start time.
6	Calculate end time	**Output Format:** Single integer value (between 1 and 48 inclusive).
		Process: 1. Calculate end time. 2. Put start and end time into matrix with the following format: Start_End_Time = [xx,xx]
7	Run vehicle model	See ‘Vehicle Transfer Energy’
8	Set discharge period for vehicle	**Output Format:** Function to replace vehicle availability with STOR discharge requirement values.
		Process: 1. Create if loop to replace vehicle arrival time with STOR discharge start time if it satisfies certain conditions. 2. Create if loop to replace vehicle departure time with STOR discharge start time if it satisfies certain conditions.
9	Stop when vehicle number is reached	**Output Format:** Simulation ends and runs into cost model

A3. GENERATE ENERGY

Use Case Name: Generate Energy
Brief Description: This use case describes the process by which the software simulates energy generation for the building from PV.
Goal: Correctly simulated energy generation in accordance with the input data and output requirements.
Success Measure: System outputs energy generation graphs relating to the selected system of interest.
Pre-conditions: • System is operational. • PV generation data is available for case study analysis required.
Typical Flow of Events: 1. Import PV generation data.

A3.1 ACTIVITY DIAGRAM FOR USE CASE "GENERATE ENERGY"



A3.1.1 DESCRIPTION FOR ACTIVITY DIAGRAM "GENERATE ENERGY"

	Activity	Description
1	Import PV generation data	**Output Format:** Average generation per building, per month per time step over 24 hours

A4. TRANSFER ENERGY

Use Case Name: Transfer Energy

Brief Description:
This use case describes the process by which the software simulates the energy available for transfer within the system to and from the vehicle.

Goal:
Correctly simulated energy movement within the system.

Success Measure:

- Energy stored within the vehicle is transferred to the building.
- Energy generated by PV within the building is transferred and stored in the vehicle or to the NG.

Pre-conditions:

- System is operational.
- Demand data is available for case study analysis required.
- Energy consumption and generation use cases are run.
- Vehicle simulate data cases are run.

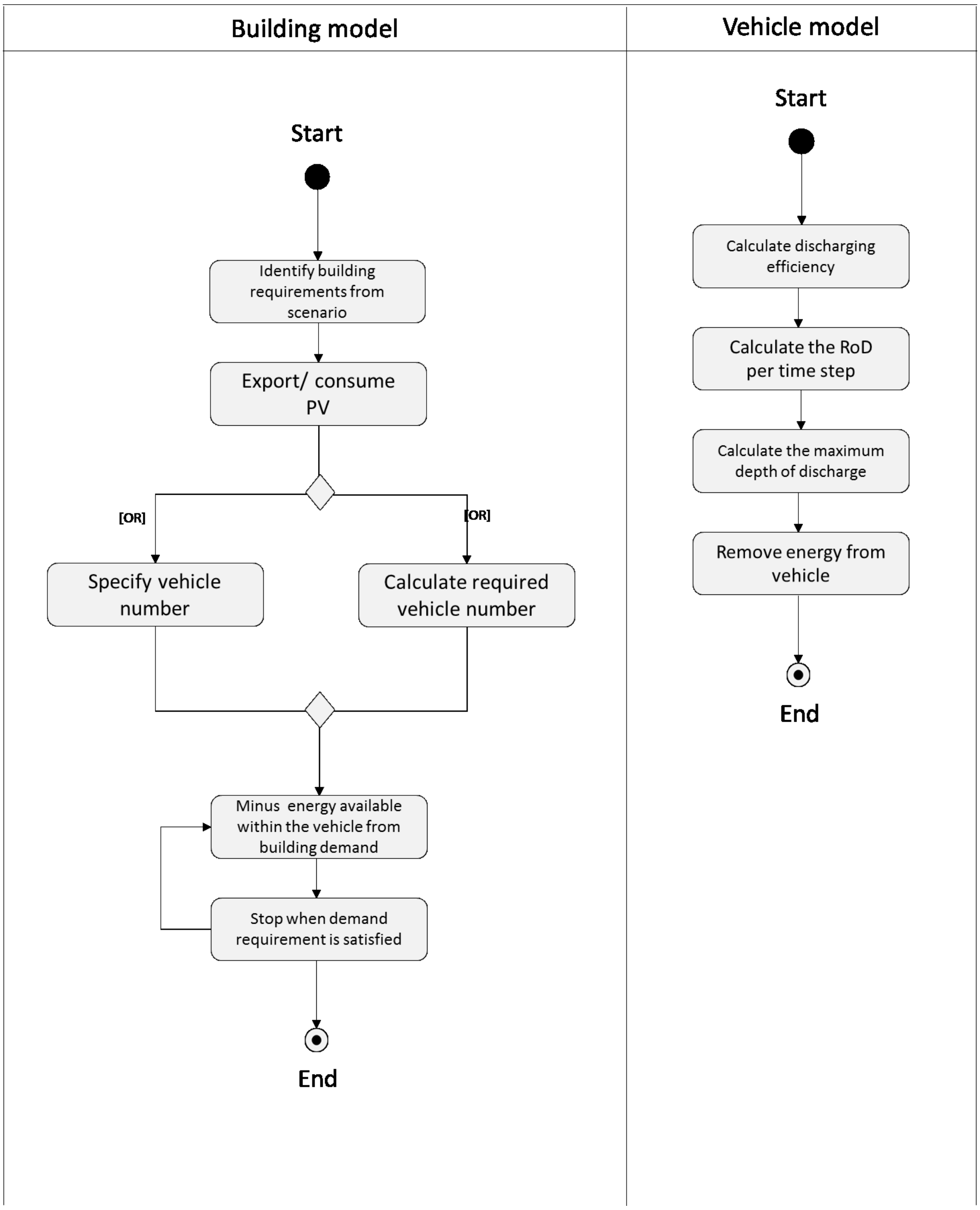
Typical Flow of Events (Building):

1. Identify building requirement from scenario
2. Export PV/ consume PV within building
    a. Specify vehicle number
    OR
    b. Calculate required vehicle number
3. Minus energy available within the vehicle from building demand
4. Stop when building demand requirement is satisfied or no more vehicles.

Typical Flow of Events (Vehicle):

1. Calculate discharging efficiency.
2. Calculate RoD per time step.
3. Calculate maximum depth of discharge for battery.
4. Remove energy from vehicle.

A4.1 ACTIVITY DIAGRAM FOR USE CASE "TRANSFER ENERGY"



A4.1.1 DESCRIPTION FOR ACTIVITY DIAGRAM "BUILDING TRANSFER ENERGY"

	Activity	Description
1	Identify building requirement from scenario	**Output Format:** Value selected from; 1.1 – 1.4 inclusive
2	Export PV/ consume PV within building	**Output Format:** New building demand matrix of kW vs time step.
		Process: 1. Using imported PV and building data, calculate new demand profile.
3A	Specify vehicle number	**Output Format:** Single integer value
3B	Calculate required vehicle number	**Output Format:** Single integer value
		Process: 1. Set threshold value. 2. Calculate current building demand per time step. 3. Simulate single vehicle discharge value. 4. Minus vehicle available from building demand. 5. Repeat until threshold value has been set.
4	Minus energy available within the vehicle from building demand	**Output Format:** Matrix with time period vs. building demand deficit
5	Stop when building demand requirement is satisfied or no more vehicles	**Output Format:** Matrix with time period vs. building demand deficit

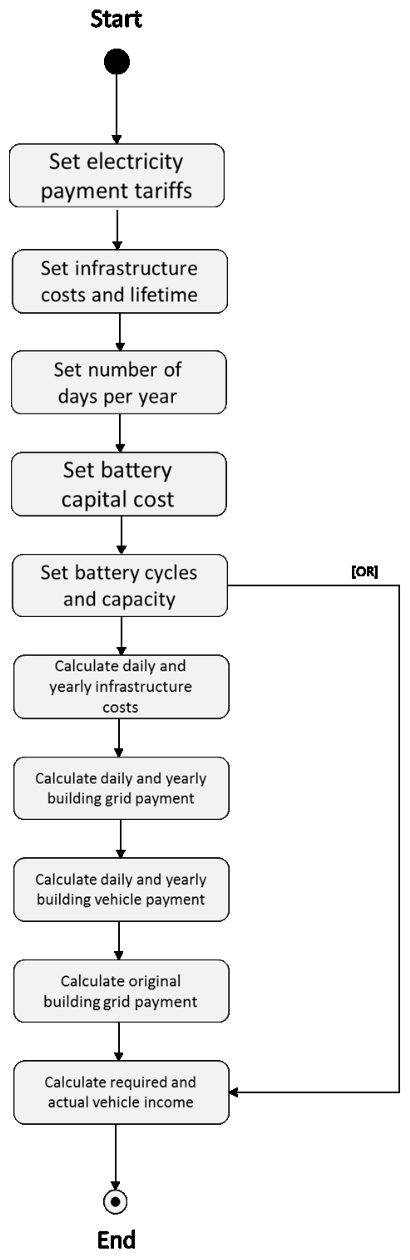
A4.1.2 DESCRIPTION FOR ACTIVITY DIAGRAM "VEHICLE TRANSFER ENERGY"

	Activity	Description
1	Calculate discharging efficiency.	**Output Format:** Select storage or supply.
2	Calculate RoD per time step.	**Output Format:** Matrix with time period vs. energy available
		Process: 1. Calculate time available. 2. Calculate energy available per time step.
3	Calculate maximum depth of discharge for battery	**Output Format:** Percentage
		Process: 1. Calculate total time available. 2. Calculate total energy available. 3. Calculate the discharge value. 4. Calculate new battery energy level (kWh).
4	Remove energy from vehicle	**Output Format:** New building demand (kW) vs. time step

A5. CALCULATE ENERGY COST

Use Case Name: Calculate Energy Cost
Brief Description: This use case describes the process by which the software calculates the associated energy costs/ profits to each actor within the software (vehicle, building and energy market).
Goal: Calculate the cost associated with transferring energy between actors within the software.
Success Measure: • Cost values are produced. • Output report is produced.
Pre-conditions: • All previous use cases are run.
Typical Flow of Events: 1. Set electricity payment tariffs. 2. Set infrastructure costs and lifetime. 3. Set number of days per year. 4. Set battery capital cost. 5. Set battery cycles and capacity. 6. Calculate daily and yearly infrastructure costs. 7. Calculate daily and yearly building grid payment with V2G. 8. Calculate daily and yearly building vehicle payment. 9. Calculate original building grid payment. 10. Calculate required and actual vehicle income.

A5.1 ACTIVITY DIAGRAM FOR USE CASE "CALCULATE ENERGY COST"

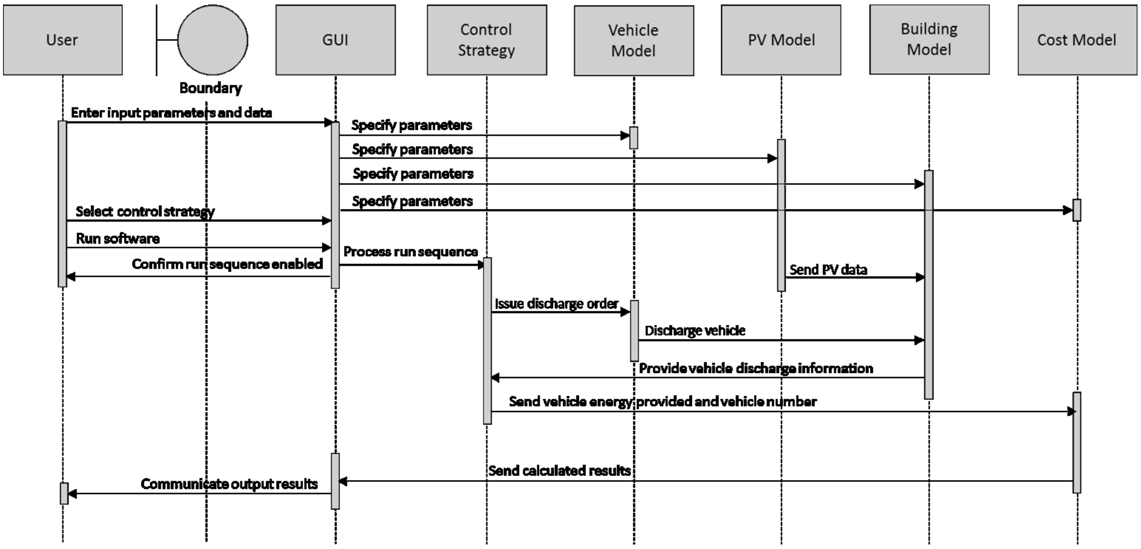


A5.1.1 DESCRIPTION FOR ACTIVITY DIAGRAM "CALCULATE ENERGY COST"

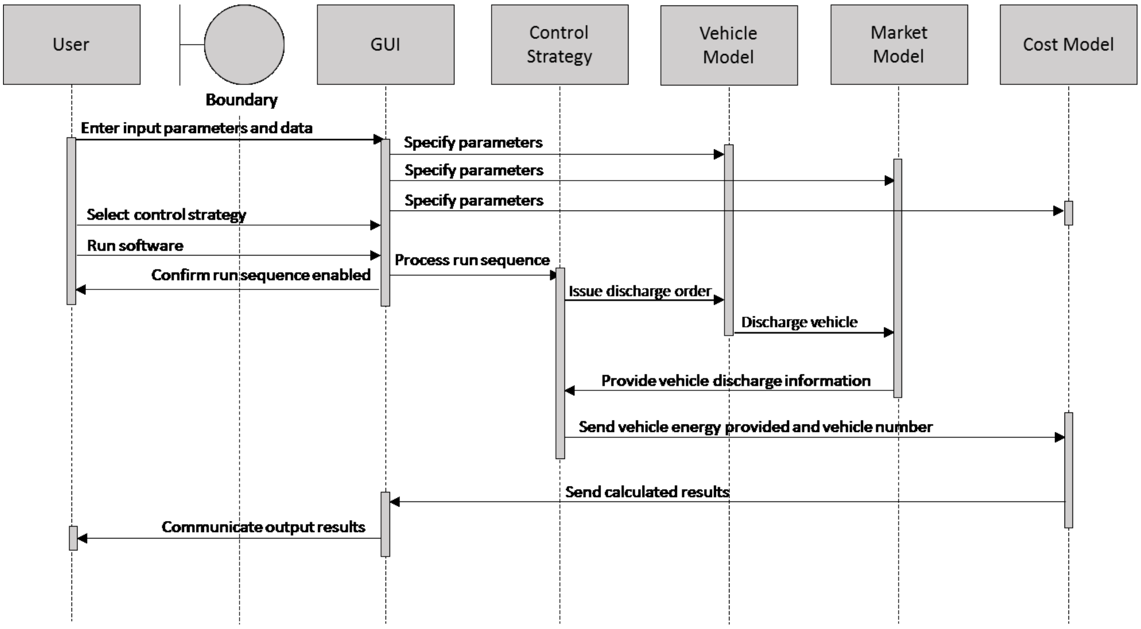
	Activity	**Description**
1	Set electricity payment tariffs	**Output Format:** £/kWh
2	Set infrastructure costs and lifetime	**Output Format:** £/kWh and years (integer value)
3	Set number of days per year	**Output Format:** Integer value between 1 and 366 inclusive.
4	Set battery capital cost	**Output Format:** £.
5	Set battery cycles and capacity.	**Output Format:** Integer value and kWh.
6	Calculate daily and yearly infrastructure costs.	**Output Format:** £.
		Process: 1. Calculate post cost per vehicle. 2. Calculate infrastructure cost per vehicle. 3. Calculate annual installation costs. 4. Calculate daily installation costs.
7	Calculate daily and yearly building grid payment with V2G	**Output Format:** £.
		Process: 1. Calculate standard grid kWh demand. 2. Calculate building with V2G grid kWh demand. 3. Calculate building grid cost per day. 4. Calculate building grid cost per year.
8	Calculate daily and yearly building vehicle payment.	**Output Format:** £.
		Process: 1. Calculate cost for energy supplied from vehicle per day. 2. Calculate cost for energy supplied from vehicle per year.
9	Calculate original building grid payment.	**Output Format:** £.
10	Calculate required vehicle income.	**Output Format:** £/kWh.
		Process: 1. Calculate increase in battery cycles due to V2G. 2. Calculate cost of additional cycles. 3. Calculate percentage DoD. 4. Calculate total energy transfer per V2G cycle. 5. Calculate cost per kWh.

A6 Sequence Diagrams

PV Model



Market Model



V2GFAE Software Validation Questionnaire – External Users

There are 21 questions to be answered covering three topics of software assessment. For questions 1-19, please circle how much you agree with the statements using a scale of 1-5, with 1 being you strongly agree to 5 being strongly disagree.

Section 1: Software Use

	Strongly Agree	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
1. The system is easy to use.	1	2	3	4	5
2. Uploading data into the software is easy.	1	2	3	4	5
3. The software speed is suitable for my needs.	1	2	3	4	5
4. The software platform is suitable for my needs.	1	2	3	4	5
5. Using the software saves me time.	1	2	3	4	5
6. Using the software increases my productivity.	1	2	3	4	5
7. It is easy to get the software to do what I want it to.	1	2	3	4	5
8. The software is overly complicated.	1	2	3	4	5
9. The software is cost effective.	1	2	3	4	5
10. The user document is easy to understand.	1	2	3	4	5

Section 2: Software Outputs

	Strongly Agree	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
11. The scenario options are suitable for my needs.	1	2	3	4	5
12. The information I get from the software is clear.	1	2	3	4	5
13. The software output report is easy to understand.	1	2	3	4	5
14. The software provides me with sufficient information.	1	2	3	4	5
15. The software outputs are accurate.	1	2	3	4	5
16. The software provides me with up-to-date information.	1	2	3	4	5
17. The software is only as accurate as the software user.	1	2	3	4	5
18. It would be useful if more analysis could be performed.	1	2	3	4	5
19. The software outputs are sufficiency for my requirements.	1	2	3	4	5

Section 3: Developmental Suggestions

20. Do you think the software has met the original stakeholder brief? (please circle) YES / NO

If NO, why not?

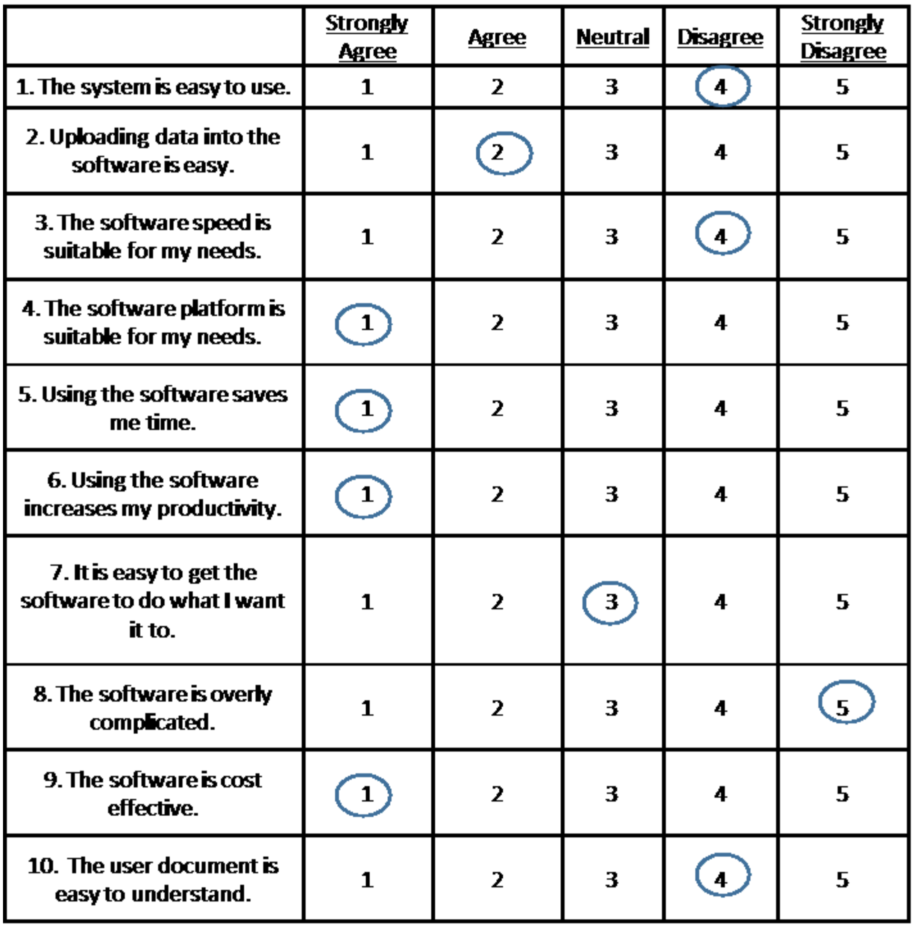
21. Please provide suggestions for improvement of the software for future versions.

The results from the two questionnaires completed by the future users of the V2GFAE are presented here.

V2GFAE Software Validation Questionnaire – USER 1

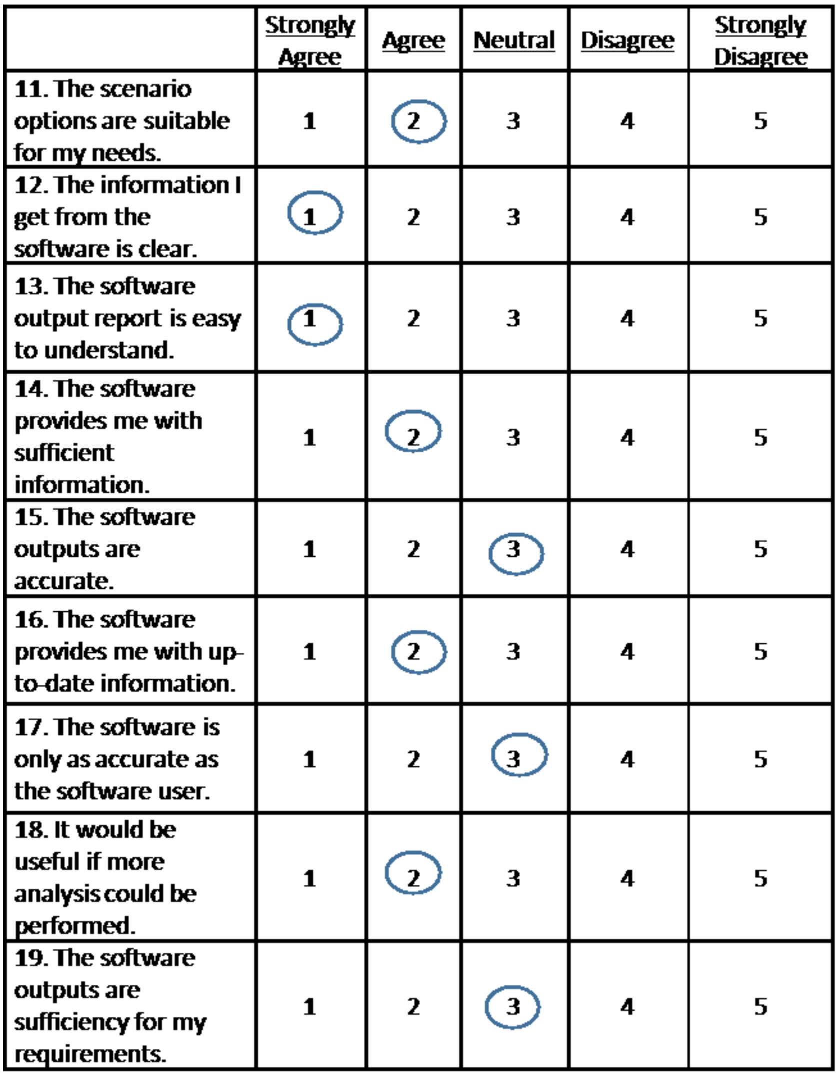
There are 21 questions to be answered covering three topics of software assessment. For questions 1-19, please circle how much you agree with the statements using a scale of 1-5, with 1 being you strongly agree to 5 being strongly disagree.

Section 1: Software Use



	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1. The system is easy to use.	1	2	3	[✓ 4]	5
2. Uploading data into the software is easy.	1	[✓ 2]	3	4	5
3. The software speed is suitable for my needs.	1	2	3	[✓ 4]	5
4. The software platform is suitable for my needs.	[✓ 1]	2	3	4	5
5. Using the software saves me time.	[✓ 1]	2	3	4	5
6. Using the software increases my productivity.	[✓ 1]	2	3	4	5
7. It is easy to get the software to do what I want it to.	1	2	[✓ 3]	4	5
8. The software is overly complicated.	1	2	3	4	[✓ 5]
9. The software is cost effective.	[✓ 1]	2	3	4	5
10. The user document is easy to understand.	1	2	3	[✓ 4]	5

Section 2: Software Outputs



	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
11. The scenario options are suitable for my needs.	1	[✓ 2]	3	4	5
12. The information I get from the software is clear.	[✓ 1]	2	3	4	5
13. The software output report is easy to understand.	[✓ 1]	2	3	4	5
14. The software provides me with sufficient information.	1	[✓ 2]	3	4	5
15. The software outputs are accurate.	1	2	[✓ 3]	4	5
16. The software provides me with up-to-date information.	1	[✓ 2]	3	4	5
17. The software is only as accurate as the software user.	1	2	[✓ 3]	4	5
18. It would be useful if more analysis could be performed.	1	[✓ 2]	3	4	5
19. The software outputs are sufficiency for my requirements.	1	2	[✓ 3]	4	5

Section 3: Developmental Suggestions

20. Do you think the software has met the original stakeholder brief? (please circle) [✓ **YES**] / NO

If NO, why not?

Yes, the software actually has more functionality than we originally discussed as it considered different markets, something I wasn't aware could be done.

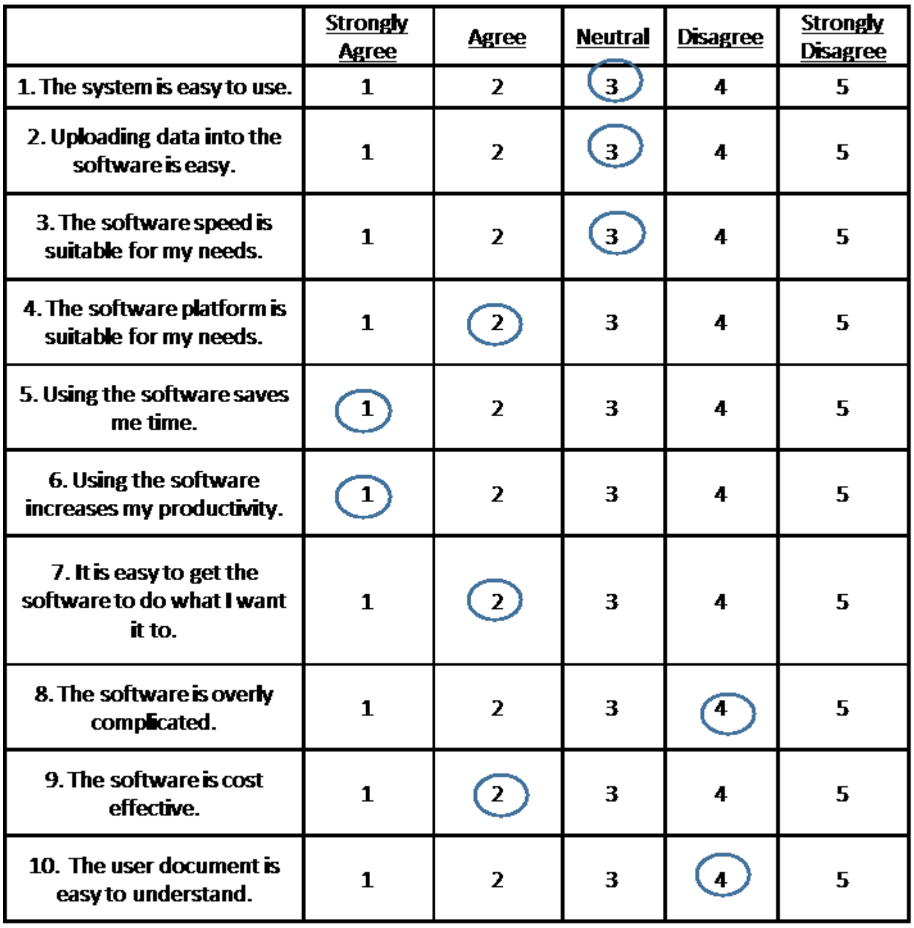
21. Please provide suggestions for improvement of the software for future versions.

It would be useful if perhaps other technology could be considered, such as battery storage, as that Is what we’re looking at in some of our research projects at the moment.

V2GFAE Software Validation Questionnaire – USER 2

There are 21 questions to be answered covering three topics of software assessment. For questions 1-19, please circle how much you agree with the statements using a scale of 1-5, with 1 being you strongly agree to 5 being strongly disagree.

Section 1: Software Use



	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1. The system is easy to use.	1	2	[✓ 3]	4	5
2. Uploading data into the software is easy.	1	2	[✓ 3]	4	5
3. The software speed is suitable for my needs.	1	2	[✓ 3]	4	5
4. The software platform is suitable for my needs.	1	[✓ 2]	3	4	5
5. Using the software saves me time.	[✓ 1]	2	3	4	5
6. Using the software increases my productivity.	[✓ 1]	2	3	4	5
7. It is easy to get the software to do what I want it to.	1	[✓ 2]	3	4	5
8. The software is overly complicated.	1	2	3	[✓ 4]	5
9. The software is cost effective.	1	[✓ 2]	3	4	5
10. The user document is easy to understand.	1	2	3	[✓ 4]	5

Section 2: Software Outputs

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
11. The scenario options are suitable for my needs.	1	2	[✓ 3]	4	5
12. The information I get from the software is clear.	1	[✓ 2]	3	4	5
13. The software output report is easy to understand.	1	[✓ 2]	3	4	5
14. The software provides me with sufficient information.	1	2	[✓ 3]	4	5
15. The software outputs are accurate.	1	2	[✓ 3]	4	5
16. The software provides me with up-to-date information.	1	[✓ 2]	3	4	5
17. The software is only as accurate as the software user.	1	2	[✓ 3]	4	5
18. It would be useful if more analysis could be performed.	[✓ 1]	2	3	4	5
19. The software outputs are sufficiency for my requirements.	1	2	[✓ 3]	4	5

Section 3: Developmental Suggestions

20. Do you think the software has met the original stakeholder brief? (please circle) **YES** / NO

If NO, why not?

Yes absolutely, it would be good if the time step were a bit shorter though, although I get that it's due to the building demand data being in 30-minute time steps.

21. Please provide suggestions for improvement of the software for future versions.

It's not that fast. It would be good if the speed were reduced, could you run multiple scenarios at the same time perhaps?

APPENDIX B

SOFTWARE OUTPUT REPORT

APPENDIX C

AUTHOR PUBLICATIONS

The following is a list of the journal and conference papers and online articles published over the duration of the research period to demonstrate the authors' academic and industry relevance.

Journal and Conference Papers

R. Gough, C. Dickerson, P. Rowley and C. Walsh, "Vehicle-to-grid feasibility: A techno-economic analysis of EV-based energy storage," submitted to *Applied Energy, 2016, London,* under review.

B. Gough, P. Rowley, S. Khan, and C. Walsh, "The Value of Electric Vehicles in the Context of Evolving Electricity Markets," in *12th International Conference on the European Energy Market, May, 2015, Lisbon, Portugal,* IEEE, 2015. pp. 1-6.

B. Gough, P. Rowley and C. Walsh, "What impact will the journey patterns of electric vehicles have on their capability to provide ancillary services?," in *The 5th IET Hybrid and Electric Vehicles Conference (HEVC 2014), Nov, 2014, London,* IEEE, 2014, pp.1-5.

P. Rowley, R. Gough, N. Doylend, A. Thirkill, and P. Leicester, "From Smart Homes to Smart Communities: Advanced Data Acquisition and Analysis for Improved Sustainability and Decision Making," in *International Conference on information Society (i-Society), June, 2013, Toronto, Ontario, USA,* IEEE, 2013. pp. 263-268.

Articles

B. Gough, "Which Electric Vehicle Use Profiles Provide Optimal Building Support Opportunities?," *IEEE Smart Cities News Bulletin,* March/ April 2015. [Online].
Available: http://smartcities.ieee.org/news-bulletin/march-2015/which-electric-vehicle-use-profiles-provide-optimal-building-support-opportunities.html

B. Gough, "The Limitations and Potential Barriers to Wide-Scale Vehicle-to-Grid in the UK?," *IEEE Transportation Electrification eNewsletter,* 15th Edition, July/ August 2015. [Online].
Available: http://electricvehicle.ieee.org/2015/08/28/the-limitations-and-potential-barriers-to-wide-scale-vehicle-to-grid-in-the-uk/