A Vehicle-to-home Simulation Tool for the Analysis of Novel Energy Storage Applications

by

Gareth Haines

Innovation Report

Submitted to the University of Warwick

in partial fulfillment of the degree of

Engineering Doctorate

August 2013

THE UNIVERSITY OF
WARWICK

Abstract

Vehicle-to-grid uses vehicles with on-board electricity storage as an energy storage system for the electricity grid. Vehicles not only take power from the grid when charging, but can supply power back to the grid. This storage mechanism can then be used in various applications, for example, providing balancing services and helping the introduction of renewable energy sources.

Research into vehicle-to-grid suggests that it is feasible in certain applications. Indeed, the component technology required for vehicle-to-grid has been successfully demonstrated. Gaps in the analysis of vehicle-to-grid feasibility remain. Notably, the behaviour of individuals in a vehicle-to-home context is not well understood.

A vehicle-to-home simulation tool was developed to address these gaps. The tool incorporates a use case methodology and a Matlab Simulink model. Application of the use case methodology identifies the inputs and constraints determined by users in a vehicle-to-home system. Feeding these inputs into the model facilitates the sensitivity analysis of vehicle-to-home operation to these user dependent variables.

The use of the simulation tool is demonstrated in two case studies: Using an electric vehicle as back-up power supply; and using an electric vehicle to support small-scale distributed generation. The operation of a vehicle-to-home system in these case studies is presented, along with the sensitivity of operation to input parameters including: battery storage capacity, vehicle usage and vehicle charging.

Both case studies demonstrated that, given the correct conditions—notably cooperation of the vehicle user—vehicle-to-home can operate successfully in storage applications. It was shown that an electric vehicle could provide back-up storage to households for a useful amount of time—between 20 hours and several days. It was shown that an electric vehicle can be used to store energy from a small-scale wind turbine such that the generation is better utilised than if no storage is available.

The developed simulation tool enables analysis of novel vehicle-to-home applications not possible with previous models of vehicle-to-grid. The use of the tool highlighted the importance of including individual variation in behaviour when studying vehicle-to-home systems.

Acknowledgements

I would like to thank my supervisors, Dr. Andrew McGordon and Professor Paul Jennings, for their discussions, difficult questions and patience; my friends at Warwick for helping make the four years there enjoyable; my family for their support; and Carolina for her help, encouragement and for making me wake early on the weekends to work on the EngD.

Thank you to John Batterbee at the ETI for taking the time to review my work.

I wish to thank the UKs Engineering and Physical Sciences Research Council (EPSRC) for its support through the Engineering Doctorate programme.

Declarations

I confirm that the work presented herein is my own unless specifically otherwise stated. All published work and sources have been acknowledged. Household electricity use data was sourced from Annex 42 of the International Energy Energy Conservation in Buildings and Community Systems Programme [1]. Wind speed data was sourced from the Royal Netherlands Meteorological Institute. Both datasets are publicly available.

I confirm that the work presented herein has not been submitted in any previous application for a degree or award.

Gareth Haines

Contents

Glossary

	Arbitrage	Storing electricity bought at a low price with the aim selling later at a higher price
	Balancing services	Services procured by the grid operator to ensure electricity supply meets demand
	Bulk storage	Large-scale energy storage placed at a single point on the electric grid
	Distributed generation	Small-scale energy generation that is geographically dispersed
	Distributed storage	Small-scale energy storage that is geographically dispersed
DoD	Depth of discharge	The percentage of the total energy capacity drawn from the vehicle battery
EV	Electric Vehicle	Vehicle using electric motor drive and battery energy storage
PHEV	Plug-in electric vehicle	Electric vehicle with a connection to the electric grid for battery charging
	Range Buffer	A user defined amount of energy stored in the vehicle battery that cannot be used for vehicle-to-grid
SoC	State of charge	Energy stored in the vehicle battery
	T&D upgrade deferral	Deferring the upgrade of constrained electric grid assets through the use of energy storage to reduce peak power levels
TRL	Technology readiness level	A framework for assessing technology development
V2G	Vehicle-to-grid	Using an electric vehicle battery as energy storage for the electric grid
V2B	Vehicle-to-building	Vehicle-to-grid specifically between several vehicles and one building
V2H	Vehicle-to-home	Vehicle-to-grid specifically between one vehicle and one building
	V2H model	The model presented herein of a V2H system developed in Matlab Simulink
	V2H tool	The tool presented herein, comprising both the use case approach and the V2H Matlab Simulink model

List of Figures

List of Tables

Preface

This document is the Innovation Report. It is the final report that, presented along with five other submissions, form the Project Portfolio of this Engineering Doctorate. Table 1 shows the structure of the Project Portfolio.

Table 1: Summary of Engineering Doctorate Project Portfolio.

Submission	Title
One	Introduction to Electric Vehicles
Two	Review of Vehicle-to-grid in Theory and Practice
Three	Vehicle-to-grid for Ancillary Services
Four	Project Dissemination
Five	Personal Profile
Six	Innovation Report

The Innovation Report can be read as a standalone document and should be read first; it describes the work carried out in the project and emphasises its innovation. The reader is referred to the other Submissions for detailed discussions on related topics:

In Submission One, electric vehicles (EVs) are introduced as an alternative to internal combustion engine vehicles. The present and future market for EVs is discussed along with a discussion of the environmental impacts of the electrification of transport. Finally, some of the challenges facing the introduction of electric vehicles are identified and discussed.

In Submission Two, the vehicle-to-grid concept is introduced, characteristics of battery storage are described and applications of battery storage are identified. A literature review of vehicle-to-grid studies is presented; both theoretical studies and practical demonstrations. Finally, barriers to the implementation of vehicle-to-grid are described based on the findings of, and gaps in, the literature.

In Submission Three, vehicle-to-grid participation in the UK ancillary services market is discussed. The operation of the ancillary services market in the UK is described along with a financial analysis of vehicle-to-grid provision of ancillary services.

Submission Four contains evidence of the application of the Project in academia and industry. A paper presented at the Ecological Vehicles and Renewable Energies (EVER) 2009 conference is included. The paper describes an early iteration of the vehicle-to-home simulation tool. The Submission also contains a letter from John Batterbee—Strategy Manager for Vehicle Integration at the Energy Technologies Institute (ETI). In the letter, Mr. Batterbee outlines his understanding of vehicle-to-home technology, praises the approach taken in this Project and states his intention to utilise the tool described herein to further the ETI's understanding of vehicle-to-home.

1

The Changing Energy Sector

In this Chapter the reader is introduced to changes driven by concerns of climate change, energy security and energy affordability. The changes required of the power sector and electricity grid are introduced, along with changes required of the transport sector.

Fossil fuels—whether used to generate electricity in power stations or used to run our cars—have become a contentious fuel source. The majority of climate scientists state that climate change is linked to man-made greenhouse gas (GHG) emissions. The Intergovernmental Panel on Climate Change have painted a stark picture of our ecological future if man-made CO_2 emissions are not reduced [2, 3]. Addressing these concerns, the UK Government agreed the legal binding Climate Change Act 2008. The act requires that by 2050 the UK emissions of GHGs are at least 80% lower than the level in 1990 [3].

Aside from the climate change argument, one cannot avoid the fact that fossil fuels are finite and non-renewable. Fossil fuels will, eventually, run out. Predicting oil reserves is not straightforward and there is much disagreement as to when oil reserves will end. However, the Hirsch report concludes that peak oil production will occur in the foreseeable future—with dire economic consequences [4]. The Carbon Reduction Strategy for Transport and the UK Low Carbon Transition Plan, both released in July 2009, outline the UK government's plans to reduce carbon dioxide emissions in transport and elsewhere [5, 6].

1.1 Electric Vehicles

Transport accounted for 75% of final consumption of oil products in the UK in 2008. Cars accounted for 58% of greenhouse gas emissions from domestic transport in 2007 [5]. The European Union has set regulation targets on CO_2 output. By 2015, the fleet average of a manufacturer's new cars must not emit more than 130 g/km CO_2 and by 2020 this target is reduced to 95 g/km [7]. The average new car sold in the UK in 2008 emitted 158.0 g/km [8]. The Society of Motor Manufacturers and Traders (SMMT) calculate that an annual improvement of 2.5% is needed to meet the EU 2015 target. The introduction of new technology will play a part in meeting the EU targets.

Electric vehicles (EVs) hold the promise of reducing carbon dioxide emissions and dependence on oil; they are therefore an avenue being explored by governments, car manufacturers and the public. UK government policy is geared in favour of eco-friendly vehicles. Using alternative fuel vehicles was stated as a strategy for "keeping our oil supplies safe and secure" [5]. The electrification of transport eliminates tailpipe emissions and dependency on gasoline and diesel fuel. The simultaneous decarbonisation of the power sector would ensure that road transport is decarbonised.

Electric vehicles have some distinct advantages over conventional vehicles:

- An electric drive train, from on-board energy source to the driving wheels, is more efficient than a conventional drive train.
- Given appropriate decarbonisation of the power sector, electric vehicles are more environmentally friendly than conventional vehicles.
- Electric vehicles have less dependence on non-renewable energy sources such as oil.
- The running costs of an electric vehicles are low compared with conventional vehicles, due to the low cost of electricity compared with gasoline*.
- From a design perspective, electric drivetrains offer greater flexibility than conventional ones.

*However, gasoline is subject to tax. This tax increases the cost of gasoline to the consumer thus increasing running costs of conventional vehicles. Electric vehicles currently enjoy government subsidies. If sales of electric vehicles increase significantly and tax receipts from gasoline vehicles fall, governments will need to review this situation.

However, several issues must be addressed because:

- There are concerns over the limited driving range electric vehicles offer compared with conventional vehicles.
- Associated with this, the charging time or refuelling time is considerably longer than with conventional vehicles.
- The lack of specific charging infrastructure is an issue.
- The financial cost of the vehicle—due mainly to the battery—is high.

Of particular interest is the electrical infrastructure that must be developed if the number of electric vehicles increases. Electric vehicles would be a new source of revenue for electricity suppliers. However, the addition of any new loads to the grid presents the problem of supplying and distributing that electricity. Further, the environmental credentials of electric vehicles depend directly on the environmental credentials of the electricity generation. The potential problems suggest the need for a smart charging infrastructure.

1.2 Smart Charging

If, as predicted, electric vehicles are adopted in large numbers, the resulting increase in electricity demand could place a significant strain on electricity infrastructure [9–13].

Specifically:

- Electric vehicles demanding electricity have the potential to push peak electricity demand above the current capacity. This is especially true if vehicles are charged simultaneously and during peak electricity demand periods.
- The electricity transmission and distribution (T&D) infrastructure may need to be upgraded to deal with demand from EVs. This effect will be amplified if EVs are concentrated in one geographical area; the local electricity distribution network may need upgrading.

The environmental credentials of electric vehicles depend directly on how the electricity the vehicle uses is generated. Depending on the mix of electricity generators used to produce the electricity that is consumed, electricity will have different environmental concerns associated with it. The environmental credentials will therefore vary by regional grid and time of charging.

Renewable energy sources exacerbate the problem as these tend to be intermittent sources. If the user wishes to charge a vehicle from a renewable source, the timing of the charge must match the availability of the source.

Smart charging of plug-in vehicles aims to address these issues. Vehicle charging could be implemented at various levels of complexity [14] and using different incentives:

Convenience charging The vehicle draws power when it is connected, regardless of any other factors.

Scheduled charging The charger is set to a timer such that the vehicle is only charged when the owner allows it. This system can be used to shift charging to times of off-peak electricity demand. Block off-peak electricity pricing (lower rates at night-time, for example) could encourage users to set their timers accordingly.

Smart charging The vehicle and charger communicate with the electricity supplier in real-time. The electricity supplier can schedule vehicle charge to ensure it does not compromise the performance of the generation side. Such a system could communicate real-time electricity pricing, automatically providing customers with cost information.

Bidirectional charging The vehicle not only charges from the grid but gives power back. This concept is known as vehicle-to-grid (V2G) and is discussed from from Chapter 2 onwards.

Convenience charging does not address the capacity, distribution and environmental issues that have been discussed—it adds to the problem. A situation where vehicle owners arrive home from work and plug in simultaneously is exactly the situation that should be avoided. Scheduled charging goes some way towards shifting vehicle charging to off-peak times but relies on decisions of the vehicle owner.

Smart charging could ensure charging takes place off-peak [10]. However, this system is more complicated and expensive in the short term—a communications and control infrastructure will need to be put in place alongside the charging infrastructure.

1.3 The Smart Grid

The decarbonisation of the power generation sector is seen as key to meeting the climate change targets [3]. The power sector is a major source of emissions in its own right. Plus the decarbonisation of the sector brings opportunities to decarbonise the transport sector via vehicle electrification and the building sector via electrification of space and water heating. Increased renewable energy generation would help decarbonise the power sector but the intermittency of renewable sources brings challenges. The electrification of transport and heating exacerbates intermittency issues. Indeed, the move to smart vehicle charging infrastructure is included in smart grid discussions.

With limited electricity storage available on the electric grid, electricity must be generated to meet demand in real-time. Figure 1.1 shows the UKs electricity demand over one day. The peak demand is nearly twice the lowest night-time demand. Power stations must be brought online and offline and have their output adjusted continuously to match generation to fluctuating demand. A failure to match generation to demand will at first manifest itself in a frequency failure. In the UK the standard mains electricity frequency is 50 Hz; a generation shortage will cause this to frequency to fall, a generation surplus will cause it to rise. As the frequency deviates from its nominal 50 Hz, appliances will start to fail. Failure to sufficiently match generation and demand will eventually result in rolling blackouts.

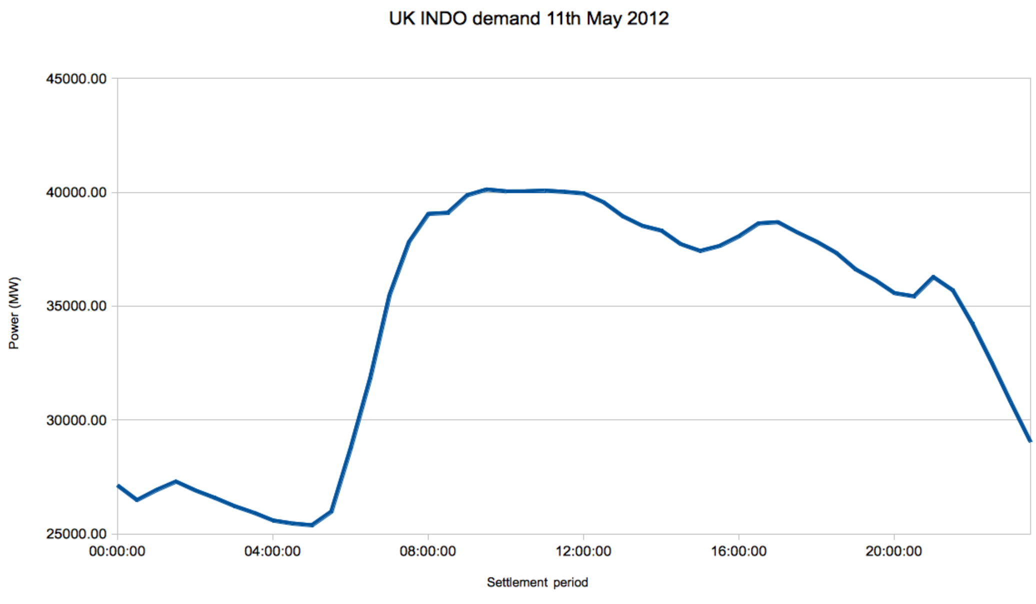

Figure 1.1: UK INDO electricity demand for 11^{th} May 2012.

Supply-side and demand-side challenges in the power sector are being addressed via the shift to a "smart grid". The smart grid seeks to improve the management and optimisation of energy demand, generation and infrastructure to help deliver the UKs long-term energy targets in an affordable way. The smart grid is a poorly defined concept, incorporating many different ideas. Broadly, the smart grid utilises ICT infrastructure alongside the existing (and upgraded) power infrastructure to facilitate several ideas that will improve grid operation. These ideas include: renewable energy generation, increased demand-side energy efficiency, demand-side management, energy storage and smart electric vehicle charging infrastructure. Once implemented, these concepts should enable the management of intermittent supply from renewable energy sources and increased demand.

Energy storage removes the problem of having to generate electricity to match demand. Energy can be stored when there is excess generation and used when electricity demand exceeds supply.

Loads with an intrinsic storage mechanism have an advantage in that they can stop demanding electricity for a period of time without losing their functionality. For example, the job of a refrigerator is to keep perishable food cool—around 1℃ to 5℃. As long as the contents of the fridge are kept within this temperature range the fridge is functional. Therefore, if the fridge is at the lower end of its temperature range and the grid frequency falls the refrigerator can stop the operation of its motor and remove a load from the grid. Conversely, the refrigerator can engage its motor to cool its contents when the grid frequency is high, increasing the load on the grid. This example falls within the variably defined concept of demand-side participation[†].

Any electrical appliance responsible for space and water heating could have intrinsic storage. As long as the working fluid is kept functionally within its specified temperature boundaries, the appliance is flexible for demand response services. In principle, the consumer will not notice (or at least tolerate) the change in appliance operation. Water must be kept sufficiently hot or cool, the ambient room temperature must be kept sufficiently warm or cool. Of course, the meaning of "sufficiently" in these statements is variable, and will likely need to be understood before any demand-side management initiatives can be implemented with success.

Electrical appliances without intrinsic storage can be used in demand-side

[†]The services that exist under demand-side participation (DSP) (often known as demand-side management) and the scope of its application have not yet been universally agreed. In this sense, DSP is not a well defined concept.

management, but their use will be more invasive to functionality. For example, the use of kettles could be forbidden when grid supply is not sufficient. Conversely, when supply exceeds demand the kettles of the nation could be instructed to operate. Of course, this situation would prevent people from enjoying a hot drink when they want one and force hot drinks upon people that are not thirsty. But technically, it is an option for ancillary services provision.

Consumer acceptance will likely be more easily achieved for demand-side participation proposals that do not limit appliance functionality. Invasive proposals would likely face consumer rejection. After all, in its current state the electricity system provides a reliable electricity supply for consumers to use as they wish. The introduction of limitations will need to be accompanied with incentives or government mandates.

There are additional barriers to the implementation of these initiatives, many are shared with the implementation of the smart grid. Controlling individual appliances or storage systems in many households or offices simultaneously would be a non-trivial IT problem, similar to the control required of smart electric vehicle charging infrastructure. Precedents for this level of control with this many appliances do exist—the internet and mobile telephone networks are examples—but these systems have significant IT/control systems that would need to be emulated. Again, the needs of the consumer should be considered, and ensuring consumers' privacy and security concerns are met by the control system will be non-trivial.

2

Introduction to Vehicle-to-grid

In this Chapter the basic concepts of vehicle-to-grid and its various forms are introduced.

Bi-directional charging technology allows smart charging to be taken to the next level; the vehicle-to-grid (V2G) concept offers an opportunity to turn the electric vehicle population into a resource [15]. With V2G the electric vehicles not only charge from the electric grid but supply power when required—electric vehicles become a distributed storage system for the electricity grid. Vehicle-to-grid can be sub classified into four different configurations—vehicle-to-home, multiple vehicle-to-home, vehicle-to-building and vehicle-to-grid.

The terminology used in this section could cause confusion; vehicle-to-grid is used both as an umbrella term for all the configurations and as a term for a configuration in itself. This problem arises because vehicle-to-grid is in its infancy—there are currently no standard definitions for terminology in vehicle-to-grid technology. The definitions adopted here are suggested by the author based on the literature [14, 15]. These definitions will be used throughout this Report.

Conceptually, vehicle-to-home is the most simple configuration of vehicle-to-grid. An electric vehicle or plug-in hybrid vehicle provides electrical energy storage to a single household or building. Each household and vehicle pair can be seen as a closed unit. Figure 2.1 shows V2H schematically; arrows indicate power flow. The stored energy in the battery provides power to the household; the electrical appliances in the building can be powered by the vehicle.

The situation becomes more complex if the closed building and vehicle units of vehicle-to-home are allowed to interact, that is, if the storage facilities of several

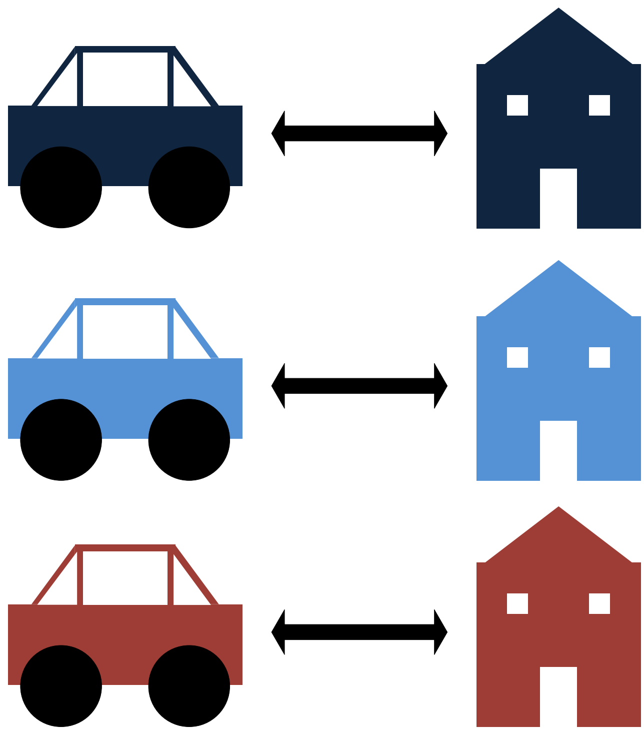

Figure 2.1: Schematic representation of vehicle-to-home.

vehicles are shared amongst several households. This concept can be called multiple vehicle-to-home and is shown schematically in Figure 2.2.

Multiple V2H could vary in scale from two vehicles serving two households to entire regions— dozens of vehicles and buildings—sharing vehicle storage. As a concept, multiple V2H benefits from “strength in numbers”; having more vehicles working together suggests that any storage needs of the electricity grid are more likely to be met. However, the shared use of vehicles as a resource will undoubtedly complicate operational and financial issues.

The term vehicle-to-building (see Figure 2.3) describes using many vehicles to provide storage for a single building—typically a large commercial building rather than a domestic household. The concept is the same as V2H except that a larger commercial building may have many more vehicles parked near to it—employees parking their cars near to their office for example.

Figure 2.4 illustrates vehicle-to-grid. Electricity is input not to a single building, but to the grid as a whole. An electric vehicle effectively becomes an electricity source for the electric grid. This is the most commonly discussed configuration in the literature.

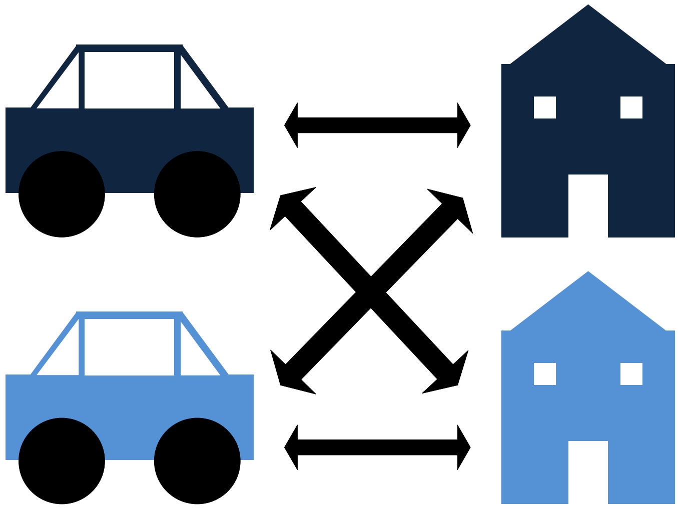

Figure 2.2: Schematic representation of multiple vehicle-to-home.

There are two reasons for classifying four different vehicle-to-grid configurations. Firstly, different configurations will be suited to different storage applications Secondly, the different configurations could be implemented with varying levels of difficulty—vehicle-to-home will be more simple to implement than full vehicle-to-grid.

The varying complexity of implementation arises because each configuration has different infrastructure and operational requirements. The configurations share some common requirements:

- An electric vehicle charging point, upgraded to allow bidirectional power flow.
- Communication with the electricity grid operator*.
- An interface to input constraints that are defined by the vehicle owner. For example, the vehicle owner may want to define the minimum level the battery state-of-charge (SoC) can fall to.

Beyond these basics, the four configurations differ in their requirements. These requirements will largely be defined by the intended storage application, but the implementation of full vehicle-to-grid will be inherently more difficult than vehicle-to-building and multiple vehicle-to-home which in turn will be more complex than basic vehicle-to-home.

The complexity arises from the number of vehicles that must be coordinated in each case. For V2H, the usage of only one vehicle and household combination need

*Although this communication may be minimal, especially in the vehicle-to-home configuration.

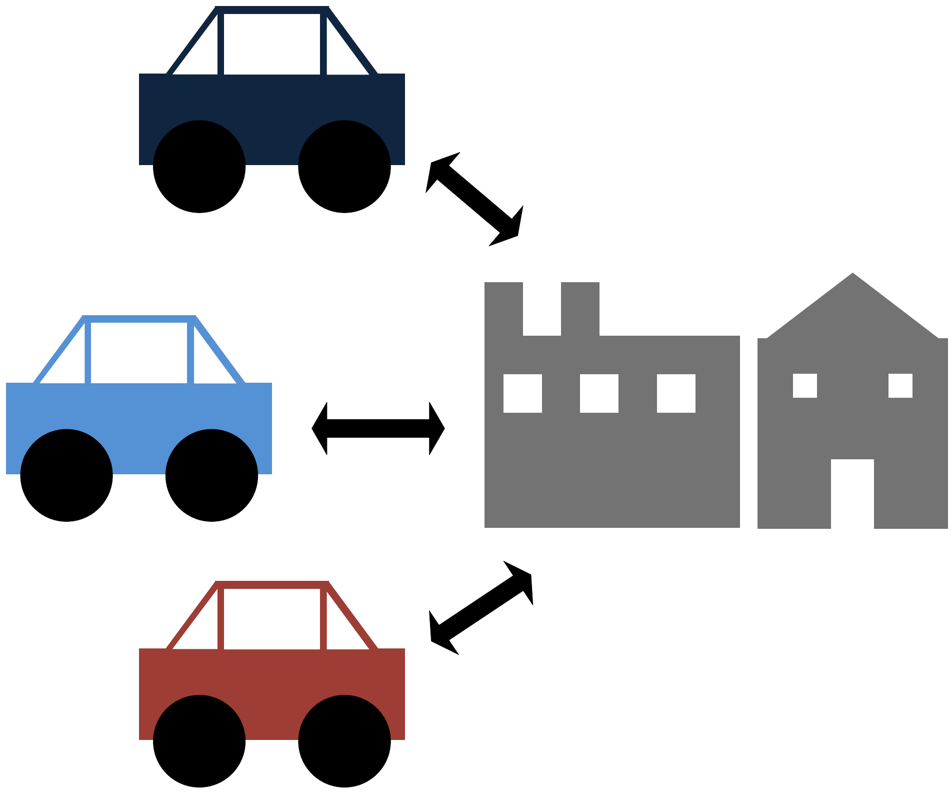

Figure 2.3: Schematic representation of vehicle-to-building.

to be coordinated. The other configurations require the coordination of more vehicles and buildings—each with their own usage patterns. Controlling these interacting systems towards a common goal—systems that are determined by human behaviour—could prove to be challenging. Indeed, attempts to quantify vehicle-to-grid systems have so far used aggregate vehicle and building usage data in their analyses for this very reason [15–17].

The coordination of infrastructure, operation and all of the legislation and regulation that will accompany them is likely to be expensive; this expense may be reduced by implementing the apparently more simple configurations if more complex ones are not necessary. The advantages and disadvantages of each vehicle-to-grid configuration should be understood based on the application requirements.

Vehicle-to-grid promises to:

- Incentivise the introduction of electric vehicles by providing a value above that of mobility; and
- aid the operation of renewable energy sources, and improve the operation of the electricity system.

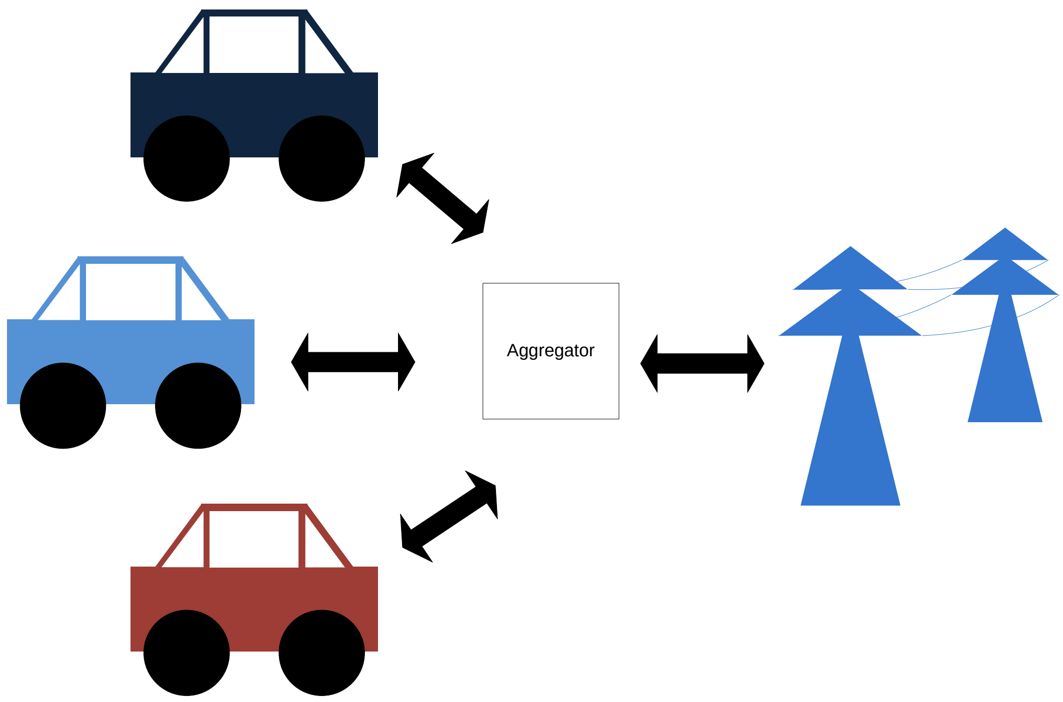

Figure 2.4: Schematic representation of vehicle-to-grid.

Two previously separate systems—the transport system and the electricity system—could be brought together because of the drivers of climate change and energy security. Vehicle-to-grid is a technology that could be realised in the marriage of the two systems; and could indeed aid the move towards both systems: By providing energy storage to the electricity system and by incentivising electric vehicles. The implementation of vehicle-to-grid technology is not without challenges. The aim of this project is to understand better the challenges faced by vehicle-to-grid and the value that it could deliver, through improving the understanding of how a vehicle-to-grid system might operate.

3

The Need for a Vehicle-to-home Simulation Tool

In this Chapter, gaps in vehicle-to-grid research are identified. This Chapter begins with a discussion of barriers to the implementation of vehicle-to-grid technology. Next, the state-of-the-art of vehicle-to-grid technology research and the need for further research to develop the technology are discussed; a Technology Readiness Levels (TRL) framework is used to structure the discussion. Both these discussions establish the need for a vehicle-to-home simulation tool; this Chapter concludes with the identification of the requirements of such a simulation tool.

The barriers that must be overcome before vehicle-to-grid and its variants can be implemented can be split broadly into technical and societal issues. Technical issues can be sub-classified as issues that prevent vehicle-to-grid from being implemented, issues of understanding that can improve the implementation of vehicle-to-grid, and technical policy. This chapter introduces these barriers and discusses some solutions.

Before electric vehicle batteries can be used for electric grid storage, there must be electric vehicles on the road—the first barrier is simply the introduction of electric vehicles. Barriers to the introduction of electric vehicles exist—improvements to the battery are particularly desirable [18]. However, the barriers specific to vehicle-to-grid are discussed in this Chapter, it is assumed (maybe unfairly) that electric vehicles will penetrate the market in significant numbers.

3.1 Technical Barriers

3.1.1 Charging Infrastructure

The introduction of electric vehicles must coincide with the development of a charging infrastructure. This basic infrastructure is a requirement for electric vehicles, but if vehicles are to be used as storage, further infrastructure will be needed.

Vehicle-to-grid charging infrastructure is different to standard charging infrastructure. The nature and extent of these differences must be understood before V2G can be implemented. The barrier is two-fold: infrastructure must be specified and installed before vehicle-to-grid is possible.

- Vehicle-to-grid requires a bidirectional power connection to the electric grid, allowing power flow to and from the vehicle. This means upgrading the vehicle power electronics. A standard vehicle is designed to accept electricity flowing to the vehicle only [19].

- The grid may need modification before it can accept a vehicle as a power source. In vehicle-to-home configuration, the building electricity network would need to be upgraded in order to accept power from both the grid and a storage device. If electricity is provided directly to the grid, care must be taken to prevent issues such as islanding, for example [20].

- Vehicle-to-grid requires a level of coordination above smart charging—extra control systems will be needed [19]. The control requirements will vary depending on the vehicle-to-grid configuration and the intended storage application.

  - Vehicle-to-home benefits from simplicity. Supervisory control will only have to coordinate a single vehicle and a single household.
  - As vehicle-to-grid expands to operate over a larger grid system, the number of vehicles and buildings that require coordination will rise. This coordination will require communication between the vehicles and buildings and the grid supervisory control.

- Several suggestions have been fielded as communications solutions, including wired and wireless communications [16].

Regardless of of charging methods and communications, standardisation of charging will be essential. Vehicle-to-grid applications require the aggregation of vehicle resources. If these resources are to be utilised effectively, the grid communication and power infrastructure must be compatible. Vehicle based storage must meet quality standards set by the grid operators. If vehicle storage is being used as a virtual power plant, modifications to the grid code (or at least specifications for the connection of a storage system to the grid) will be required. The feed-in specifications of distributed energy systems (e.g. G83 [21] or G59 [22] regulations) could be the starting point.

All of these factors must be considered as vehicle-to-grid infrastructure requirements are specified. Appropriate specification will aid in the implementation of vehicle-to-grid, but the infrastructure will need to be put in place. This raises ownership issues—who will build and maintain vehicle-to-grid infrastructure? Who will own the batteries and account for their degradation due to V2G use?

3.1.2 Understanding the Resource

Vehicle-to-grid makes an electric vehicle a potential resource for the electricity grid. The storage it provides can potentially be used in a variety of applications, as discussed. In order to exploit vehicle-to-grid most effectively, its nature as a storage resource must be understood.

In some respects, V2G storage can be classified in the same way as stationary storage. When the vehicle is plugged in to a charging point it is essentially the same as a stationary battery of the same specification. However, as previously mentioned, vehicle-to-grid storage operates under constraints that stationary storage avoids. It is the impact of these constraints that needs to be understood.

Vehicle usage determines the availability of the vehicle and the SoC of the vehicle battery. How, where and when a vehicle is used determines how useful it is for vehicle-to-grid once it is plugged in. For example, a vehicle that is never plugged into the grid will never be used for vehicle-to-grid, the other extreme is a vehicle that is never used in its primary function.

Electricity storage is used as a service to the electricity grid, the way the service is used will therefore depend on the grid and the demands placed upon it. The two major factors in determining the effectiveness of vehicle-to-grid are therefore the use of the subject vehicle and the state of the grid it aims to serve.

Previous studies have considered vehicle-to-grid using average data [15, 16, 18, 19, 23, 24]. While this is an informative way of looking at vehicle-to-grid and an indicator of its feasibility, it has weaknesses.

Average data is only helpful when studying large-scale vehicle-to-grid applications, that is, vehicle-to-grid with many vehicles working together. On a smaller scale, from vehicle-to-home up to tens of vehicles serving a non-national scale electricity grid, average information concerning the use of vehicles and the demands of the grid are not valid. Vehicle-to-home, as the most extreme example, cannot be studied using average data—the use of the individual vehicle and the individual household electricity use must be considered. The use of aggregate data may underestimate the potential of vehicle-to-grid as a resource in niche applications [24].

This means that the major studies in V2G feasibility are only valid once electric vehicles penetrate the market in large numbers. A more thorough analysis of vehicle-to-grid would look at vehicle usage in more detail [20] and electricity usage (or the services required by the electric grid) in more detail. This implies that models should consider individual vehicles and buildings and build from there. Further, this requires more more granular data—individual vehicle usage data and electricity data from individual buildings, recorded more frequently.

An understanding of vehicle-to-grid that is built up from single vehicles and single buildings can be generalised and compared with results from the average case at a later point. This process will also make clear when it is appropriate to use average data and when individual cases must be studied i.e. *how much* better an understanding of the resource is required and when.

3.1.3 Application

As a storage system, vehicle-to-grid could be used in various applications. The intended storage application will influence the configuration—vehicle-to-home, vehicle-to-grid or some intermediate of the two. The barrier is the determination of which application vehicle-to-grid is best suited for and in which configuration. Broadly, a vehicle-to-grid configuration with an aggregator can be considered bulk energy storage; a vehicle-to-home configuration can be considered distributed energy storage.

Certain V2G configurations lend themselves to different applications*. Potential applications are matched with vehicle-to-grid configurations in Table 3.1.

*The reader is referred to Submission 2 for a description of each storage application

Table 3.1: Potential matching of applications with vehicle-to-grid configurations.

Storage Application	**Configuration**			
	V2H	multi-V2H	V2B	V2G
Arbitrage	✗	✗	✗	✓
Capacity	✓	✓	✓	✓
Balancing Services	✗	✗	✗	✓
Reactive Power	✓	✓	✓	✓
Transmission Support	✓	✓	✓	✓
T&D Upgrade Deferral	✓	✓	✓	✓
Substation	✓	✓	✓	✓
Cost Management	✓	✓	✓	✗
Back-up Generation	✓	✓	✓	✗
Power Quality	✓	✓	✓	✗
Renewable Energy Integration	✓	✓	✓	✓
Load Management	✓	✓	✓	✗
T&D Losses	✓	✓	✓	✓

The proposed matching of applications to V2G configurations is based upon the possible power flows from the vehicle to the different grids represented in each configuration. However, the conclusions presented in Table 3.1 do not take all of the factors into account. It is necessary to test whether vehicle-to-grid is both feasible and beneficial in each application, and necessary to test which application and configuration works best in a given situation.

Previous studies have overwhelmingly focussed on using vehicle-to-grid for the provision of ancillary services and aiding the introduction of renewable energy. A comprehensive study would analyse vehicle-to-grid and its variants in other storage applications.

Potentially, the most valuable storage applications for vehicle storage are on the distribution network level. For example, if the physical infrastructure of a distribution network is near its capacity limit, the infrastructure may need to be replaced at significant cost. Energy storage can be used to shift the peak electricity demand on this distribution network and defer the need for infrastructure upgrade. This application of distributed energy storage is potentially more valuable than bulk energy storage [25].

The vehicle-to-home configuration is most applicable in this situation (fewer vehicles, embedded on a distribution network, are required)—the current modelling approaches to not allow for this valuable application to be studied in detail.

3.1.4 Revenue

Revenue from vehicle-to-grid has been studied for balancing services and renewable energy integration applications in the US, largely by Kempton and associates [15–17, 19, 23, 26].

Kempton and Tomíc found that V2G is well suited to frequency response services. Frequency response services are high value, require fast response from the storage device but require only shorter sustained energy flow from the storage. Vehicle-to-grid has fast response to calls for energy and the short timescale energy requirements ensure that the vehicle battery is never deep-discharged, preserving battery life. The high value of frequency services tip the economics in favour of vehicle-to-grid.

Peak power services (reserve services and load following during peak demand periods) were found to be only marginally profitable for a vehicle-to-grid user [16].

Using vehicle-to-grid in the place of baseload generation was found to be unfeasible by Kempton [16] but Turton and Moura suggested that it may be feasible [24].

The limitations of these studies are similar to those described in Section 3.1.2. Average data are used to test the economics of vehicle-to-grid. A fuller economic analysis would take account of vehicle-to-grid in all potential applications and judge each scenario on its own merits.

3.1.5 Costs

Arguably, using electric vehicle charging infrastructure for vehicle-to-grid services above the simple charging requirement increases the wear and tear on the system. Increased wear and tear will reduce the lifetime of components and force an early repurchase, driving up costs.

This is a pertinent issues for the battery. Increased use of the battery beyond its primary function (mobility) may degrade the battery and reduce its operational lifetime. If this is the case then the revenues generated from vehicle-to-grid services must outweigh the costs incurred through degradation. The Kempton studies estimate the impact of battery degradation on cost, but do so, inevitably, on an averaged basis.

It has been suggested that vehicle-to-grid may even extend the life of the battery [27] though this has not been proven in publicly available documents. The lifetime extension may result from heating within the battery through V2G usage that counters the damage of cold weather during winter operations.

Prediction of the battery degradation incurred through use is difficult and varies by battery chemistry. However, to improve these predictions it is necessary to characterise the exact requirements that V2G places on a battery. That is, detailed power versus time duty cycles that result from vehicle-to-grid provision are required. The previous models do not provide this, only indicating a total energy requirement on the battery over an extended period of time.

3.1.6 Geography

Much of the research into vehicle-to-grid has been based in the United States. The Danish EDISON project appears to be comprehensive in its approach, but is yet to publish any major findings.

In 2008, the Department for Business, Enterprise and Regulatory Reform (BERR), the Department for Transport (DfT), Arup and Cenex published a joint study into the introduction of electric vehicles and plug-in hybrid vehicles in the UK [10]. As part of this, vehicle-to-grid was studied.

The report claimed, through discussions with electricity utilities, that, initially, vehicle-to-home is a better concept than large scale vehicle-to-grid. Additionally, the study demonstrated that arbitrage was not an economically viable vehicle-to-grid application. This was primarily due to the high capital cost of batteries.

The BERR and DfT study was not comprehensive in its review of vehicle-to-grid, and it represents the only (publicly available) UK based vehicle-to-grid research.

3.2 Societal Barriers

It has been argued that the social, cultural and political barriers to plug-in vehicles and vehicle-to-grid are more significant than the technical ones [18].

3.2.1 Capital Costs

Societal issues come back to the purchasing of electric vehicles, in particular, the problem that people tend to be influenced by up-front cost of a vehicle more than the running costs [18]. This is bad for electric vehicles, where the up-front cost is higher than an equivalent conventional vehicle, but the running costs are lower. Government subsidies help tip the balance towards electric vehicles, but the issue remains.

This issue may hamper vehicle-to-grid. Even if, as previous studies have suggested, vehicle-to-grid proves to be financially beneficial for the vehicle owner in the long term, up-front costs associated with the conversion to vehicle-to-grid may be off putting to consumers. These discussions are hypothetical for two reasons. The cost benefit analyses carried out so far are only guidelines to the feasibility of vehicle-to-grid. Also, ownership of electric vehicle batteries and V2G related costs and revenues is still the subject of discussion; different business models will change the cost of vehicle-to-grid for the vehicle owner.

Indeed, it has been noted that vehicle-to-grid—if it is economically viable—could encourage the sale of electric vehicles. The high initial capital costs would be offset by the increased revenue from viable vehicle-to-grid applications.

3.2.2 Human Variation

Vehicle use, electricity use and vehicle charging are inherently human activities.

Vehicle use determines the availability of the vehicle for V2G duties and the energy stored in the battery at any given time, both of which will effect the operation of vehicle-to-grid. Electricity use is also variable based on human activity.

However, the transport and electricity networks are both mature systems. The human variation in both cases is at least recognised and measurable. When the two are combined—as is the case with electric vehicles and particularly vehicle-to-grid—the human behaviour is relatively unknown. That is, the lack of electric vehicles on the road makes the human behaviour associated with EV ownership an unknown. Many EV pilot schemes around the world could address this issue.

While the charging schedules of vehicles can be influenced by the electric grid (using financial incentives and penalties, for example), short of mandatory charging controls, people will charge their vehicles when they please. Indeed, a user may not plug their vehicle in at all if they deem it charged "enough"; this scenario would render vehicle-to-grid impossible. The variability and predictability of human behaviour in this sense needs to be understood.

Vehicle-to-grid relies on vehicle owners making their vehicles available to the grid. The presentation of theoretical financial and environmental benefits to potential V2G participants may be enough to win their support, but the actual vehicle-to-grid behaviour may differ from the expected and promised.

3.2.3 New Technology

Plug-in vehicles and vehicle-to-grid are nascent technologies. Traditionally, new technologies are approached with caution by all but a few early adopters; this presents a problem for vehicle-to-grid because it may require mass adoption in order to succeed [18].

In order to convince vehicle owners that vehicle-to-grid is beneficial to them, it is essential that the benefits and drawbacks of V2G are outlined to potential participants in an unbiased manor—without interference from parties with perceived bias and ulterior motives.

Such new technology may face up to institutional barriers. Vehicle-to-grid would not only change the way the transport system and electricity system operate, it would change the concept of the two systems and how they interact. It has been suggested that there could be institutional opposition to a vehicle-to-grid transition [18]. This suggestion is based upon accounts of institutional opposition to new technology in the past, in particular, opposition to electric vehicles in California in the 1980s. Sovacool and Hirsch suggest that opposition to EVs and V2G may come from automobile manufacturers, oil companies and automotive repair services—any party with interests in the conventional vehicle infrastructure [18].

Honda have explicitly expressed opposition to vehicle-to-grid, stating that Honda electric vehicles are not designed to be electricity storage devices and that consumers should buy Honda generators if they require distributed generation [28].

These suggestions highlight the need to understand exactly how vehicle-to-grid might operate and who it will affect—both positively and negatively. Parties that appear to benefit from vehicle-to-grid may oppose it. Electric utilities stand to be a main beneficiary in a vehicle-to-grid transition. However, a high penetration of V2G into the market stands to decentralise the electricity network—electric utilities will need to be convinced of the benefits of this [24].

3.2.4 Resistance to Change

Vehicle-to-grid represents a marked change from traditional vehicle ownership. Vehicle owners may resist this change, particularly if it requires large changes in their vehicle usage or large effort on their part.

For example, it is unlikely that a typical vehicle-to-grid participant will want to (or be able to) spend time calculating ideal charging and discharging times based on information from electricity suppliers—the system must be automated.

However, some manual control must remain. Range anxiety is often cited as a problem in electric vehicles; vehicle-to-grid exacerbates this problem. In the author's experience, a primary concern that is raised in vehicle-to-grid discussions is that the electric vehicle will have all of its energy removed for vehicle-to-grid services when the vehicle is required for a journey.

Suitable control hardware and software are potential solutions to this problem. A vehicle-to-grid controller must be sufficiently automated to give the vehicle owner a good deal, while allowing them the ability to manually override any discharging that might take place. The inclusion of what Kempton calls a "range buffer" will prevent the vehicle from having its energy removed from its battery, rendering it useless in its primary function.

3.2.5 Business Models

Value could be gained from vehicle-to-grid energy storage in a variety of ways depending on the application the grid operator is willing to serve. There are questions that must be answered along the value chain. It is not clear where the value of the storage can be realised (and where it cannot). To properly analyse the value chain and the potential of different business models requires an understanding of vehicle-to-grid system operations in detail (both in time and by customer).

For example, variable electricity pricing tariffs could be used in vehicle-to-grid operations to encourage the user to offer a service at a given time. These can only be properly designed and tested for feasibility if there is knowledge of the variation of the vehicle owner/operator (variation in the suitability of the storage) and knowledge of the variation of the requirement for the storage (from the grid side).

Vehicle-to-grid opens the possibilities for innovative new business models and value chains. But these cannot be explored using the models of V2G operation that have been constructed to date. The problem is exacerbated by the use of public charging points. A vehicle identification system would be required if the vehicle owner is to be reimbursed for vehicle-to-grid services from a public charging point. Vehicle-to-grid could be applied in various different scenarios, for example, large parking areas represent a potential vehicle-to-grid resource and a different resource to a single vehicle providing vehicle-to-home. Different potential V2G scenarios should be identified and tested for feasibility in different applications and V2G configurations.

Ownership is an important issue in a V2G business model. In particular, ownership of the battery itself will raise questions. If the storage is being used for the benefit of a third party then the battery owner must be compensated for providing the service. This is especially true if using the vehicle battery for vehicle-to-grid causes the battery to degrade more quickly (and therefore reduce the useable battery lifetime).

Warranty and insurance issues will likely arise—it is not clear that the vehicle manufacturer will honour a vehicle warranty if the battery is used for anything other than its primary use.

Again, innovative ownership models could be used. Ownership of the vehicle battery could fall on the stakeholder that gains most value from vehicle-to-grid, with the battery being leased to the vehicle operator for mobility use. These ownership models can only be explored if the operation and value of vehicle-to-grid is well characterised, and as argued, it will only be well characterised once the aforementioned barriers have been addressed.

3.3 The Wider Context

Technology is generally developed in stages: From an idea and a "back of the envelope" calculation through to full commercialisation, with several development stages in between. Technology Readiness Levels are a systematic framework for discussing the maturity of technology along development stages [29]. An understanding of the maturity of a technology helps establish a focus for future research; using an established framework helps socialise† this discussion.

The US National Aeronautics and Space Administration (NASA) developed

†Provides a defined and consistent basis on which to conduct discussions.

the original Technology Readiness Levels framework and have formally used the framework in their technology planning processes since the 1990s [29]. The US Department of Defense (DoD) modified the NASA TRL framework for use in its own projects and the US Department of Energy (DoE) (slightly) modified the NASA and DoD TRL frameworks for use in energy related technology assessments [30]. The US Department of Energy TRL framework is presented in Table 3.2.

Table 3.2: US Department of Energy Technology Readiness Level Framework.

Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	TRL 9	Actual system operated over the full range of expected conditions	The technology is in its final form and operated under the full range of operating conditions
System Commissioning	TRL 8	Actual system completed and qualified through test and demonstration	The technology has been proven to work in its final form and under expected conditions
	TRL 7	Full-scale system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment
Technology Demonstration	TRL6	Engineering-scale system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment
Technology Development	TRL 5	Lab-scale system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to the final application in almost all respects
	TRL 4	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish the the pieces will work together
Research to Prove Feasibility	TRL3	Analytical and experimental critical function and/or proof of concept	Active research and development is initiated; this includes analytical studies and lab-scale studies to physically validate the analytical predictions of separate elements of the technology
Basic Technology Research	TRL2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented; applications are speculative and there may be no proof or detailed analysis to support the assumptions
	TRL 1	Basic principles observed	Scientific research begins to be translated into applied R&D; examples may include paper studies of a technology's basic properties

According to the framework, technology development can be characterised as TRL 1—"Basic Principles Observed through to TRL 9—"Actual System Operated Over Full Range of Expected Conditions. The leftmost column of Table 3.2 summarises the TRLs into more familiar language: Basic Technology Research, Research to Prove Feasibility, Technology Development, Technology Demonstration, System Commissioning and System Operations.

Technology Readiness Levels are an aid to [31, 32]:

- Establishing a common understanding of technology status;
- inform risk management:
  - Technology risk—failure of a technology through insufficient development; and
  - investment risk—making decisions on technology funding or aquisition;
- make decisions concerning insertion of technology; hence
- highlighting gaps in development and suggesting focus for further research.

The US agencies will not use a technology until it is satisfied that the technology has reached a certain maturity, according to the TRL assessment. The US Department of Defense expects that technologies are TRL 6 or above before proceeding to contracts for manufacturing.

In the UK Technology Readiness Levels are used by organisations including the Society for Motor Manufacturers and Traders (SMMT) and the Technology Strategy Board (TSB) [32].

Technology Readiness Levels have limitations:

- TRLs assessments can be subjective (though do provide a systematic way of assessing a subjective issue);
- the suitability of a technology within its relevant system is not necessarily considered; and crucially
- market acceptance of the system is not necessarily considered.

Therefore, barrier identification must complement the TRL analysis to identify non-technology development that must take place along with technology development.

The US Department of Energy Technology Readiness Level framework is used here to discuss the maturity of vehicle-to-grid technology. Figure 3.1 shows the major studies in vehicle-to-grid technology placed on the US Department of Energy Technology Readiness Levels framework.

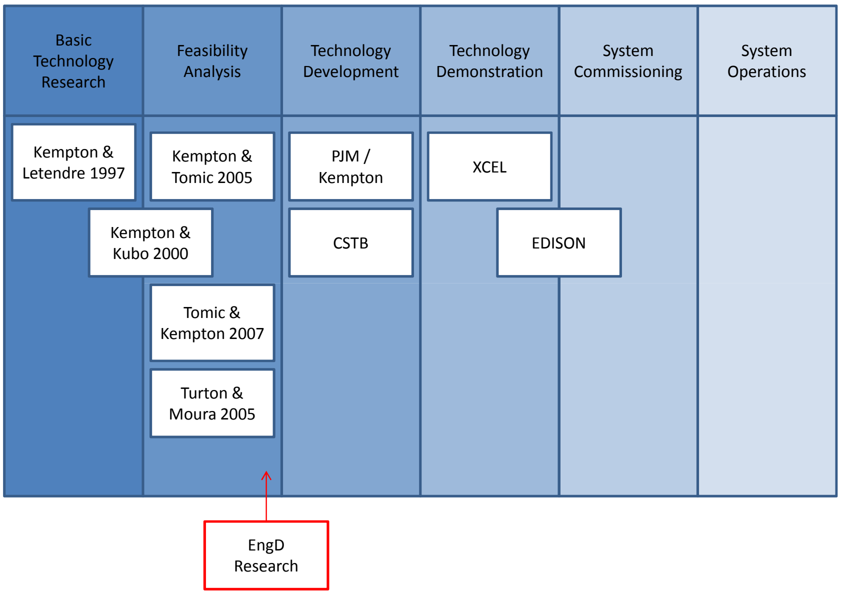

Figure 3.1: EngD research and major vehicle-to-grid research placed on US DoE TRL framework.

Broadly, the stages should progress from left to right in Figure 3.1; this has not quite been the case. Research in the field jumped straight from feasibility analysis into the technology development phase a vehicle-to-grid demonstration—the development of the component technology so that an electric vehicle could be connected to the grid and used in the provision of ancillary services [33, 34].

Component technology risk will not be the concern with vehicle-to-grid. Technology development is ongoing, and vehicle-to-grid bi-directional charging has been demonstrated [33, 35, 36]. The introduction of electric vehicles, or lack thereof, may indeed be a risk to vehicle-to-grid technology. But again this is not solely a technological issue.

Investment risk is more significant for vehicle-to-grid. The technology exists to operate a V2G or V2H system, but it is yet to be proven that operating such a system is operationally or economically feasible. The potential system, its reliance on human behaviour and the business models that result are not well understood.

3.4 Research Objectives

Research into vehicle-to-grid has progressed to the technology development stages as if the technology is at Technology Readiness Level 4-6. However, there remain barriers to the implementation of vehicle-to-grid that are best addressed at the feasibility analysis stage.

Models that enable an assessment of the feasibility of vehicle-to-grid are presented in the literature. The hypothesis is that existing models do not describe vehicle-to-home in sufficient detail to ascertain its feasibility. The lack of detail can be summarised as:

1. Existing models do not allow a time-series analysis of the use of vehicle storage for vehicle-to-grid and therefore do not capture variation due to people's behaviour. Existing models are only capable of using average data as inputs and so are only valid for assessing the feasibility of vehicle-to-grid when many vehicles are available for use as storage; existing models cannot be used to assess the feasibility of vehicle-to-home on an individual case by case basis.

   Kempton, Letendre and Tomic([15] and elaborated on in [16, 17]) model the available power per vehicle (for vehicle-to-grid) as in Equation 3.1[‡].

   $$P = \frac{\left(E_{\mathrm{s}} - \frac{d_{\mathrm{d}} + d_{\mathrm{rb}}}{\eta}\right)}{t} \tag{3.1}$$

   where P is the power available from the vehicle, E_{s} is the energy stored in the vehicle battery, d_{d} is an average driving distance, d_{rb} is a range buffer distance and t is the time the vehicle is parked and available for vehicle-to-grid.

   The operation of a vehicle-to-home system depends on when the vehicle is parked, connected to the grid and on how much energy is available in the vehicle battery; these factors are captured in Equation 3.1, but the changing status of the vehicle with time is not captured. Equation 3.1 is then used as a basis for calculating revenue from electric vehicles supplying ancillary services to the electric grid.

   Kempton *et al.* [16, 17] use an average journey distance and range buffer are used in the calculation of vehicle-to-grid feasibility; time available to provide

[‡]Assuming power flow from vehicle to the grid is not further limited by the surrounding infrastructure.

vehicle-to-grid is assumed based on the finding that vehicles are parked over 95% of the time. But Equation 3.1 cannot account for *when* the vehicle is available and if the vehicle can provide vehicle-to-grid services when they are required.

Kempton *et al.* account for the fact that electric vehicles are not always parked by assuming more vehicles are contracted to provide a storage service than is necessary. For example, if each vehicle in a fleet can provide 15kW of power to the grid then, strictly, 67 vehicles are required to provide 1MW of power total. The authors assume that 100 vehicles would be able to supply this 1MW total even accounting for vehicle use and vehicles requiring charging or maintenance. It is suggested that vehicles can earn revenues from participating in ancillary services. This suggestion is based on average driving distance, range buffer and vehicle parking duration assumptions.

Turton and Moura [24] model a vehicle providing vehicle-to-grid services as a power source that is available 50% of the time. The authors note that 50% is a conservative estimate of availability compared with the 96% availability suggested by Kempton *et al.* but timing of availability is not considered in the Turton and Moura approach.

2. Existing models are only suitable for analysing the feasibility of vehicle-to-grid in applications where vehicle storage is aggregated.

   In [16, 17] the revenue and cost of using vehicle-to-grid in the US ancillary services markets and in support of wind and solar generation are calculated.

   Vehicle-to-grid could be used to store wind energy when wind generation exceeds demand and to supply demand when wind generation is low. To a lesser extent, solar power may benefit from having energy storage to allow the matching of electricity supply and demand. The models used by Kempton *et al.* [16, 17] and Turton and Moura [24] estimate a bulk requirement for energy storage to support intermittent supply over extended periods of time.

   For example, in [17] the authors cite analysis that suggests the operating reserve requirement for wind (to support low wind events) is 11% of installed wind capacity. That is, 100GW of installed wind capacity would require 11GW to be available from vehicles providing vehicle-to-grid services. The authors then calculate the number of vehicles required to provide this service using average data to calculate power available from the vehicles and the multiplication factor to account for vehicle availability. Similar models are used to calculate the number of vehicles required to support wind generation under more stringent capacity requirements. Additionally the authors note that, statistically, low wind events are short. They present measured data that suggests 60% of low wind events are less than 2 hours long; vehicle storage would be required for less than 2 hours in 60% of these events.

The provision of ancillary services is modelled in a similar way to the provision of wind support. The bulk requirements for ancillary services are estimated for any given time. The number of vehicles that, when aggregated, could provide the required power to the grid is then calculated.

Note that Kempton *et al.* are conservative in their estimates of the feasibility of vehicle-to-grid. The models used in the literature suggest that when many vehicles are aggregated the energy stored in the vehicle batteries can be economically used to provide high value ancillary services and to support intermittent renewable energy generation.

However, the models in the literature do not allow the analysis of limited numbers of vehicles offering vehicle-to-grid (or vehicle-to-home where a single vehicle is considered) in distributed energy storage applications. The models are therefore not yet valid because there are not many electric vehicles on the road and capable of participating in vehicle-to-grid services. Vehicle-to-grid systems will likely start with smaller numbers of vehicles participating, before large aggregated services are offered. It would be useful to consider vehicle-to-home as a sensible starting point.

Further, distributed energy storage can offer services that aggregated bulk storage cannot. These distributed storage applications are higher value than bulk storage applications [25]. The models presented in the literature cannot be used to study distributed storage applications; they therefore miss out a potentially favourable application for vehicle-to-home and small scale vehicle-to-grid services.

The models of vehicle-to-grid must be improved so that the feasibility of the concept can be clearly established, only then should research progress confidently to the next stages of technology readiness.

A model that enables a better understanding of vehicle-to-grid as a resource and gives the flexibility to study different applications of vehicle-to-grid and vehicle-to-home will in turn allow the following barriers to be addressed:

- Improved analysis of revenue and costs in various applications;
- a basis for the development and testing of innovative business models; and
- information for testing the consumer acceptance of vehicle-to-grid (i.e. presenting realistic, evidence based information to consumer to allow them to make informed decisions.)

The hypothesis suggests a different approach to those employed in the previous desk-based studies is required. The research objectives that test this hypothesis are therefore:

- Develop an approach to modelling vehicle-to-home that enables a sensitivity analysis of user determined inputs and their granularity;
- Demonstrate that this approach can be used to study distributed storage applications that could not be studied with previous approaches;
- Demonstrate this approach in a vehicle-to-home system such that it provides outputs not possible with previous approaches; and
- Describe the differences, or lack thereof, of this and previous approaches.

3.4.1 Required Scope

A simulation tool consisting a model of vehicle components and system; with a consideration of different stakeholders and variation of their behaviour; and the ability to run multiple simulations; would allow the gap in the understanding of the feasibility of vehicle-to-grid to be addressed.

The following scope of the work required to develop such a tool is proposed, based on the discussions from the preceding literature review, gap analysis and barrier identification sections. The scope of work required can be summarised as developing a tool with improved granularity of inputs, improved flexibility regarding inputs and simulation capability allowing the flexibility to repeat and compare studies, as follows:

Granularity: In terms of the treatment of individual of vehicles being modelled and the input of time-series data to describe the use of the vehicles and infrastructure.

- The tool should be capable of simulating the base unit in vehicle-to-grid—a single vehicle interacting with an electrical infrastructure. This requires a model that represents the infrastructure corresponding to a single vehicle and its charging system i.e. a vehicle-to-home system.
- The tool should be able to simulate realistic user behaviour and the variation/uncertainty that results in the system. This requires the ability to use time-series data—data that is specific to the individual in question and includes variation with time. The following parameters are not time-series in previous models, the importance of them being granular should be exlplored:
  - Power drawn from the vehicle battery for driving use;
  - power available from the vehicle battery for the provision of vehicle-to-home services (including if the vehicle is connected to the grid);
  - the resulting energy changes in the battery storage; and
  - power required by the infrastructure for the chosen storage application.

Flexibility: To simulate and compare potential applications of vehicle-to-grid on an individual case-by-case basis:

- Granular model inputs must be input in such a way that changing these inputs to examine different individual cases is a simple and consistent process, such that two cases can be compared equitably.
- The model must be sufficiently flexible as to simulate different demands from the generation sector (or, more generally, from the electricity supply infrastructure) that are associated with providing the storage service for the given application. For example, if the vehicle-to-home system is required as a back-up electricity supply, the power required by the household is of interest; if the vehicle-to-home system is to be used to support wind generation, the power supplied from the wind turbine is of interest.

Simulation: The ability to repeat and compare studies requires a simulation function; that the granular and flexible model can be used to study the operation of the system over time and in with different sets of inputs. Simulations should be quick enough that multiple cases can be run in a reasonable period of time.

If a model begins with a single vehicle and a single household as its supporting infrastructure, it can be used to simulate vehicle-to-home. This model can then be repeated and expanded to simulate more complex vehicle-to-grid configurations. The key is to allow the variation of the infrastructure surrounding the vehicle.

4

Design of the Vehicle-to-home Tool

In the previous Chapter, the requirements of the V2H tool were proposed based on the need for a new modelling approach, as inferred from the literature review. The V2H simulation tool was developed to address these requirements and therefore meet the identified need. In this Chapter, the design of the tool such that it meets the defined requirements is described. This Chapter begins with a discussion of some practicalities—how the tool should model the necessary physical systems*. Next, specific aspects of the design that address the tool requirements are discussed.

4.1 Use Cases

The scope of the previous Section is a useful starting point, but must be developed more fully before they can be meaningfully implemented in a simulation tool. Detailed requirements analysis was structured using a use case methodology [37]. Use cases are commonly used to analyse requirements in complex systems engineering projects (and are common in complex software development projects). A scenario (or group of scenarios) in which the proposed system may be used is described at a high level. All the stakeholders in the system scenario are identified and the role of each stakeholder (or "actor" in UML† parlance) within the system is determined. The interactions of

*A note on terminology: The "Tool" refers to the model and the approach taken to establish the use of the model and data input to the model, that is, model plus use case analysis and data acquisition; "Model" refers specifically to the model developed in Matlab Simulink.

†Unified Modelling Language (UML) is a standardised general-purpose modelling language, used to visualise the different aspects of a complex IT systems project.

each actor within the system—communication between actors and of actors with different parts of the system—are then established in the chosen scenario. The definition of actors is quite general: They can be humans (or organisations) that use the system or machines that form the system.

The use case methodology can and has been used in the various projects that are captured under the smart grid umbrella. The Electric Power Research Institute (EPRI) has developed a use case methodology for smart grid applications [38]; numerous example use cases have been submitted to EPRI and are available in the resource repository[‡]. The repository contains examples of the EPRI use case methodology applied to vehicle-to-grid and vehicle-to-home. The EPRI use case repository is not an academic peer reviewed journal, however, use cases that are created in smart grid projects are reviewed by EPRI before they are made publicly available on the repository. Since EPRI is a well-respected organisation in its field, use cases from its repository are useful (if only as a guide to thinking). It is worth reviewing the EPRI vehicle-to-home use case for two reasons:

(a) To demonstrate the use case methodology by example; and

(b) to initially identify the actors in a vehicle-to-home system and the interactions of actors in the system.

Use cases are introduced with a "narrative" to explain the situation being described. The EPRI vehicle-to-home use case example is quite general. "The customer wants to use the energy stored in their PHEV[§] to optimise their load at their premise. . . to support customer distributed energy resource. . . or charging or discharging during a demand response event". The scenario is V2H support for distributed generation such as solar or wind power and/or responding to a call from the electricity supplier to provide ancillary services.

Table 4.1, Table 4.2 and Table 4.3 are reproduced (almost verbatim) from "PEV as Storage Scenario"—the use case scenario that describes vehicle-to-home in general (without a specific grid application) [38]. Table 4.1 lists the stakeholders or actors involved in a V2H system; Table 4.2 describes the scenario at a high level; Table 4.3 lists the interactions between actors.

[‡]http://www.smartgrid.epri.com/Repository/Repository.aspx (accessed 2nd July 2012)

[§]PHEV defined as plug-in hybrid electric vehicle or pure electric vehicle.

Table 4.1: Actors within a vehicle-to-home system; EPRI.

Actor name	Actor type	Actor description
Charger	Device	Power electronics that allow the charging of the battery. The charger can either be on-board the vehicle or off-board.
Clearinghouse	Organisation	Organisation that provides electric vehicle account services. Maintains the information for account validation and billing validation (if the utility is not providing this feature).
Control device	Device	Dynamic control gives the utility the ability to remotely control charging equipment.
Customer	Person	The operator of the electric vehicle.
Customer account	System	Account assigned to the customer to manage charges for billing of energy usage.
Customer Energy Management System	System	For the communication of vehicle information (e.g. state of charge, charging rate, time to full SoC) to the customer.
Electric vehicle supply equipment (EVSE)	Device	Electric vehicle connects to the grid via EVSE—the physical cord and connectors.
Energy portal (UK–Charging point)	Device	A charging point for an EV (a power outlet).
Energy Services Interface (UK–Smart meter)	System	Enables secure interactions between Home area network devices and the utility.
End use measurement device	Device	Measures and communicates energy usage information to ESI. (An accurate measurement device, probably integrated into the smart meter)
Energy service company (ESCO)	Organisation	Alternative supplier to established electric utility.
Electric vehicle	System	Connects to a charging point to draw power; transport means that requires electricity for propulsion.
Roaming utility	Organisation	Electricity supplier that supplies vehicle power outside of the customers home territory.
Utility	Organisation	All the systems, business functions and organisations that supply electricity on the retail market.

The presented EPRI application of the use case methodology is supposedly for a simple case of vehicle-to-home—it is also based on a system in the United States, given the terminology in use. The EPRI use case identifies several grid-side parties and the expectation that the grid-side may have control over V2H operation. This is to cater for the expectation (as stated in the narrative) that the EPRI use case describes demand response events, that is, a single-vehicle-single-household vehicle-to-grid system. The use case also caters for distributed renewable energy support, a pure vehicle-to-home application.

The use case methodology has several benefits:

- It entails a more detailed consideration of the requirements of a system, and therefore of the simulation of that system.
- It lends structure, consistency and thoroughness to the identification of model

Table 4.2: High-level description of vehicle-to-home scenario; EPRI.

Triggering event	Primary actor	Pre condition	Post condition
Customer plugs vehicle into energy portal (charging point)	Customer	Customer has PHEV and Customer Energy Management System that interfaces with PHEV	Customer has successfully operated their PHEV in optimizing load at their premise

Table 4.3: Step-by-step interactions between actors within a vehicle-to-home system; EPRI.

Step	Actor	Description of step
1	Customer	Customer connects PHEV to energy portal at their premise location
2	PHEV	PHEV senses power to on-board charging unit and begins charging or discharging based on operator selected preferences
3	PHEV	PHEV binds with customer energy management system
4	Customer energy management system (CEMS)	CEMS executes program that controls PHEV charging/discharging to optimise load at premise
5	Customer energy management system	CEMS sends control signals to PHEV requesting PHEV information and energy storage parameters (ie. PHEV ID, storage capacity, state-of-charge, charging rate, discharging rate etc.)
6	PHEV	PHEV returns to CEMS PHEV information and energy storage parameters
7	Customer energy management system	CEMS sends control signals to PHEV requesting charging/discharging to optimise load at premise
8	PHEV	PHEV processes control messages sent from CEMS and executes them after verifying request against current vehicle parameters
9	PHEV	PHEV sends message to CEMS confirming control message and PHEV status
10	PHEV	Customer disconnect PHEV from energy portal
11	Customer energy management system	CEMS senses session has ended and terminates program that controls PHEV charging/discharging to optimise load at premise

requirements; the resulting requirements should be more rigorously defined than if requirements are defined in an ad-hoc manner.

- It lends consistency to the presentation of the requirements; consistency of presentation should make the requirements identification process easier to understand and therefore open to criticism and, in turn, more rigorous.
- It prompts the engineer to consider the system from the point of view of the stakeholders (rather than only from the physical system). Since the vehicle owner/operator is a stakeholder in the system, his needs and the uncertainty arising from his behaviour will be considered and accounted for.

The use case methodology could be applied in the order presented by EPRI:

With the identification of actors followed by the interactions between actors required in a given process. Alternatively, a consideration of the process that the system needs to deliver should enable the identification of required actors. The difference is subtle: The former method is more conservative with actors identified because they are expected to be required in the system; the latter is more radical with actors only included if they are necessary to deliver the system. Vehicle-to-grid is a new concept that will be delivered within an established system (with established actors). It may therefore be difficult to implement a radical system of actors, even if the setup is sufficient or superior. For example, the EPRI use case names the electric utility as an actor. Since their definition is kept general it is difficult to refute that *some* organisation will supply power to the vehicle, but it is not necessarily the electric utility or supplier setup that exists at present that will do this job. It is indeed possible that if consumers move to become "prosumers"[¶] that the role of the utility will change considerably. The energy system is changing and will likely continue to change in response to external drivers. Vehicle-to-grid system developers may be given the opportunity to build a system from scratch.

In the remaining Chapters the design of the tool will be described and its use in simulating several V2H applications demonstrated. The design of the tool will begin with a description of the necessary physical systems—the actors that are basic components—in a vehicle-to-home system. A use case approach will then be employed to describe the role of the actors within the system and determine the detailed requirements of a vehicle-to-home tool.

4.2 Structure of the Simulation Tool

The V2H model consists of main systems that participate in a vehicle-to-home application (the actors within a V2H/V2G system that are critical to its operation). Three participating systems must be considered in a vehicle-to-home system: vehicle, building and generation.

The structure of the model within the simulation tool is shown conceptually in Figure 4.1. Generally, the tool accepts inputs, processes these input data in some decision making process and outputs some information. Finally, the outputs can be

[¶]Producers of electricity as well as consumers from the grid, for example, using distributed renewable energy generation that supplies the grid system.

interpreted in the right context, this stage is described in Figure 4.1 as "Insights".

Inputs and control are described in this Chapter. The process of using tool outputs to gain insights will be described once the tool is used in the case study examples presented in Chapters 5 and 6.

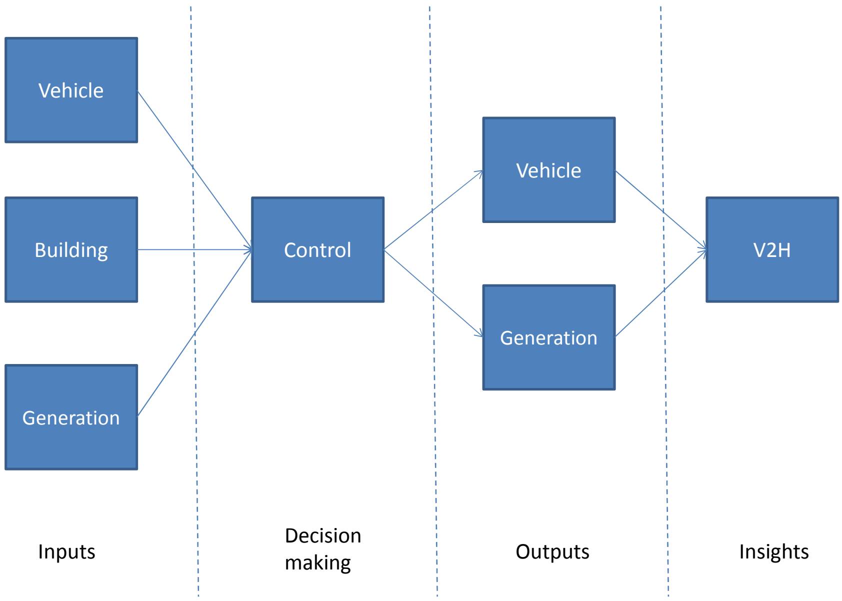

Figure 4.1: Conceptual diagram of the simulation tool; showing key systems and input, processing, outputs and insights stages.

The need to include a "vehicle system" is clear—the vehicle is a key feature of a vehicle-to-home system‖. The "vehicle system" comprises a vehicle with on-board electricity storage and the associated charging infrastructure. In vehicle-to-home terms, bi-directional power electronics and a connection to a grid are required along with the appropriate vehicle.

The "building system" comprises the building infrastructure that directly surrounds the vehicle. This will differ in scale depending on the vehicle-to-grid configuration being investigated and its intended application. For example, in a vehicle-to-home simulation, the building infrastructure is the household that the vehicle is connected (plugged in) to; from the vehicle perspective the household is the "electric grid" that the vehicle is providing V2H services to. The term "building"

‖If the vehicle in the V2H system is never used for transport then the vehicle is similar to a stationary storage system. The tool is used to study an essentially stationary storage system in a later case study.

generalises this argument to include commercial properties, work offices etc. The need for a specifically classified "building system" arises from a particular vehicle-to-home application. A vehicle-to-home configuration could provide power to household appliances from the vehicle battery rather than from the grid; the reasons for doing this range from back-up power supply to grid demand balancing. To simulate this application, the usage of electrical appliances within the building electrical system must be simulated, hence the need for a "building system". In some applications, the electrical appliances that directly surround the vehicle are not of interest and the "building system" is largely redundant; this will be discussed as necessary in the case studies.

The "generation system" comprises infrastructure upstream of the vehicle and building unit—distribution, transmission and generation included. This infrastructure is varied and vast, and is therefore treated with some generality or, more specifically, the key infrastructure within the "generation system" is identified for each case study to which the tool is applied. The generation system will vary in nature, in scale and in specification depending on V2G configuration and application. Specific generation system simulation will be discussed in each of the case studies; the generation system is the most variable of the three systems, in terms of how it is modelled within the simulation tool. However, the general approach to simulating the generation system is consistent across simulated applications, as should become apparent.

Applying the use case methodology the system actors can be defined in more detail. The EPRI use case narrative described above is general, but to ensure that the application of the use case methodology results in a tool that addresses the barriers, the use case methodology should be applied with respect to the barriers. The general use case narrative for the design of the vehicle-to-home tool is: "The customer (vehicle operator) has competing needs of mobility and the use of vehicle energy storage to optimise their load at their premise to support some function that benefits either themselves or a third party." Note that more specific narratives will be written for subsequent case studies.

With a narrative that has more focus on the needs of the consumer and a generic approach to the application of V2H (compared to the EPRI narrative), the system actors are slightly different. The actors are presented in Table 4.4. The system actors are described in UK terminology.

Table 4.4: Actors within a vehicle-to-home system.

Actor name	Actor type	Actor description
Customer	Person	The operator of the electric vehicle.
Electric vehicle	System	Connects to a charging point to draw power; transport means that requires electricity for propulsion.
Charger	Device	Power electronics that allow the charging of the battery. (Defined here as including the necessary grid connections/charging point)
Control device	Device	Controls the operation of the vehicle and charger systems to allow the appropriate use of storage (includes any necessary smart metering/accurate metering devices).
Customer Energy Management System	System	For the communication of vehicle information (e.g. state of charge, charging rate, time to full SoC) to the customer.
Electrical appliances	Device	The household appliances that, when operated, comprise the household electrical load.
Household Energy Management System	System	For the management of the household appliacnces.
Electricity supplier	Organisation	The entities that enable the delivery of electricity via the grid; in the UK this is structured as supplier, distribution network operator and transmission operator.
Distributed generator	Device	A generator, local to the household, that may require support from V2H storage.

The next stages of the use case methodology—describing the scenario and describing interactions between actors—are not useful at this stage of design. The use of the tool in the case studies of Chapters 5 and 6 will be a natural place to use these stages of the use case.

Building on the dual functionality argument, the key vehicle factors in V2H are:

- The availability of the vehicle;
- the battery state-of-charge at a given time; and
- the future state-of-charge requirements of the battery.

The key grid / grid operator factors in V2H are:

- The energy and power available for ancillary services;
- the timing of the available energy; and
- the technical capability to provide the service.

Other factors must be considered by the grid operator and the vehicle owner (and other parties)—factors that will determine the economic feasibility of the situation and overall environmental considerations. Once the operational detail of V2H is characterised the economic and environmental details can be investigated in detail. The first step is to understand if vehicle-to-home *can* feasibly participate in ancillary services and the detail of the operation; the second step is to find out if it is worth doing. The tool developed for this EngD project will focus on the operation. The outputs of the model will inform on the operational feasibility of V2H in various applications. The economic and environmental ramifications of such operation will be discussed in limited detail in this Innovation Report. It is intended that the results and methods presented in this report will enable other parties to investigate the economic and environmental feasibility of Vehicle-to-home in more detail.

4.3 Modelling Platform

Matlab Simulink was chosen to develop the vehicle-to-grid model. There are several reasons for this:

- Matlab is a popular programme for engineering applications. A model is only useful if it can be used, and choosing a commonly used programme increases the chances of this.
- A physically accurate model will not be created (the reasons for this are discussed throughout the document), rather, the model will manipulate data in a "black box" fashion; the model must be capable of taking input data and processing it arithmetically to produce the desired outputs (V2G feasibility, ultimately). Matlab is suited to this type of data manipulation. If a physically accurate model was going to be developed, a model specifically designed for electrical systems modelling would be used.
- The model must be capable of simulating decisions influenced by human behaviour. Stateflow—a part of Simulink—is well suited to decision making models.
- Matlab is capable of manipulating large data sets—larger than Excel, for example—allowing data sets recorded over long periods of time and/or with highly granular data to be used. Granularity was identified as a key factor and a differentiator in this model compared with others, so the management of large dataset is crucial.

The physical systems are modelled in Simulink and Stateflow. Matlab scripts are used to load data into Simulink and to automate some model processes. Matlab arrays are the preferred data format—arrays can be fed into the model or out of the model. Data manipulation and the presentation of results is also done in Matlab—graphs etc.

Units of energy and power will be used in the model operation and analysis, rather than the electrical units: charge, voltage and current etc. This choice is fundamental to the operation and focus of the model—by choosing energy units, the operation of the model is constrained in some regards, but flexibility and applicability is increased in others. A model based on energy and power is a valid one and is most appropriate in meeting the desired model requirements:

- The model must simulate three different systems—vehicle, building and generation—that must interact seamlessly within the model. Using energy and power units to describe the three systems aids its modularity and flexibility.

- Vehicle-to-home describes the conversion of electrical energy to and from chemical energy for storage purposes. Energy units are consistent across different energy forms and can be used to describe inter- and intra- system conversion in a consistent manner. Using energy units rather than electrical units ensures the model is flexible, standardised and straightforward when describing different energy forms.[**].

- Generation systems also convert some form of energy to electrical energy. Consistency and flexibility in the simulation of conversions is important in the generation system as it was in the vehicle (storage) system.

- Economic analyses and the quantification of environmental impacts are discussed in terms of power and energy. This model is being developed chiefly to aid feasibility analysis and as a decision making tool so, at some stage, the model outputs must be quantified in economic and environmental terms. This quantification will be straightforward if the outputs are described in energy units; the outputs will be more useful for parties that want to analyse the feasibility of vehicle-to-home.

[**]If the model is expanded to consider vehicle-to-grid with vehicles that use other storage mechanisms, for example, hydrogen fuel-cell vehicles or plug-in hybrid vehicles, then this flexibility regarding energy conversion will be a very useful feature.

However, the use of energy units does constrain the model:

- Electrical units are sometimes used in the electric vehicle battery modelling literature (including manufacturing data). In some characterisations, electrical and energy units are used together—both are valid, of course. A flexible approach must be taken: If an electrical unit is most appropriate then it will be used, with appropriate explanation.

- Some phenomenon that could arise in the grid system require the simulation of how voltage and current interact—of the complex phase relationship between voltage and current in the electrical circuit. A model based on energy units cannot simulate vehicle-to-home applications that focus on voltage and current phenomena. For example, a vehicle-to-home system could operate to modify reactive power within the electrical system—the simulation of reactive power phenomena requires a consideration of the phase relationship between voltage and current in the AC system.

4.4 Physical System

The components of the physical systems required for vehicle-to-home were modelled in Matlab Simulink. The Simulink model was organised by subsystems as shown in Figure 4.2—organised as Generation Subsystem, Household Subsystem, Vehicle Subsystem and V2H Management Subsystem. The Vehicle Subsystem and V2H Management Subsystem together model the flow of power into and out of the vehicle battery and how this power flow is managed for V2H applications. The Vehicle Subsystem and V2H Management Subsystems do not change depending on the vehicle-to-home storage application being studied. The Generation and Household Subsystems do change depending on the V2H application. The Generation and Household Subsystems will therefore be described further in the two case studies presented in Chapter 5 and Chapter 6.

4.4.1 Vehicle Subsystem

From a vehicle-to-home perspective, the most important component in an electric vehicle is the battery. A vehicle-to-home model need only simulate the vehicle battery and the power electronics needed to use this battery as energy storage. There are of

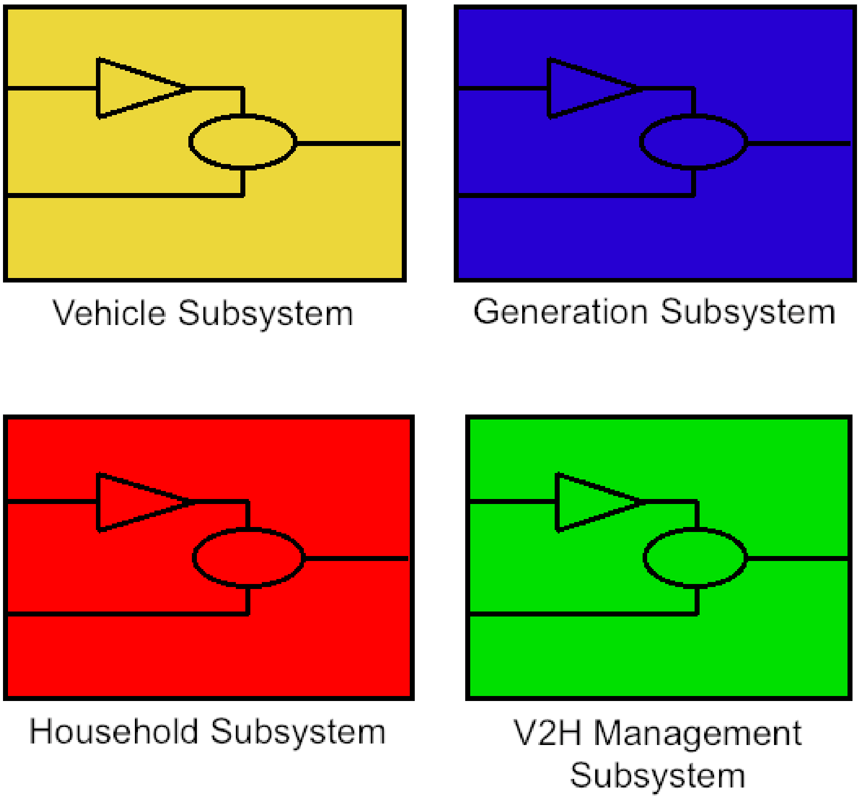

Figure 4.2: Generation, Household, Vehicle and V2H Management Subsystems in Simulink.

course other systems in an electric vehicle, the traction motor and auxiliaries, for example, but these are not directly of concern in vehicle-to-grid simulation. Indirectly, all the vehicle systems are of interest because all the vehicle systems will influence the usage of battery energy during driving. Vehicle driving usage will be treated as a time-varying parameter and is discussed in Section 4.5.

The physical parameters that must be included in the vehicle simulation are summarised in Table 4.5.

Table 4.5: Summary of physical parameters to be simulated for a vehicle.

Parameter	Summary description
Battery energy (kWh)	The energy available in the battery (limited to a maximum capacity)
Battery charging efficiency	The fraction of electrical energy input to the battery that is stored as chemical energy in the battery
Battery discharge efficiency	The fraction of stored chemical energy that is converted to useful electrical energy
Efficiency—power electronics	The fraction of input and output power during power electronics conversions
Battery degradation	The permanent loss of battery storage capacity that occurs through age and use

Equations 4.1, 4.2 and 4.3 describe the relationships between these parameters.

$$\frac{\Delta E}{\Delta t} = P \tag{4.1}$$

where ΔE is the change in battery energy, Δt is the timestep and P is the power to/from the battery.

$$\frac{P}{P_{charge}} = \eta_{charge} \tag{4.2}$$

where P_{charge} is the power into the battery before accounting for efficiency losses and η_{charge} is the battery charging efficiency.

$$\frac{P_{discharge}}{P} = \eta_{discharge} \tag{4.3}$$

where $P_{discharge}$ is the power from the battery after accounting for efficiency losses and $\eta_{discharge}$ is the battery discharging efficiency.

Figure 4.3 shows the Simulink model used to simulate power flows to and from the battery. Power flow to the battery during charging is $PCharge$ and is controlled via a switch and the $Chargingtime$ input; when $Chargingtime$ takes the value 1 the power flows to the battery. Power flow from the battery is shown as a separate subsystem to facilitate ease of upgrade if driver behaviour modelling of the tool is improved. Currently, the power draw versus time is input as an array. $PAppfromcar$ is the power flow from the vehicle to the household (app being an abbreviation of appliances). $PAppfromcar$ is a calculated parameter depending on whether the vehicle is required for vehicle-to-home, or not, and is discussed in Section 4.4.4.

Battery Capacity—Energy and Power

A vehicle battery has a finite energy capacity. This constraint must be simulated by the model, the model can then respect the constraint during simulated operation. The finite energy capacity of a battery governs the amount of energy that can be transferred to and take from the battery.

Additionally, the model requires several inputs that can be used to determine how battery capacity varies with battery usage, the three most influential factors

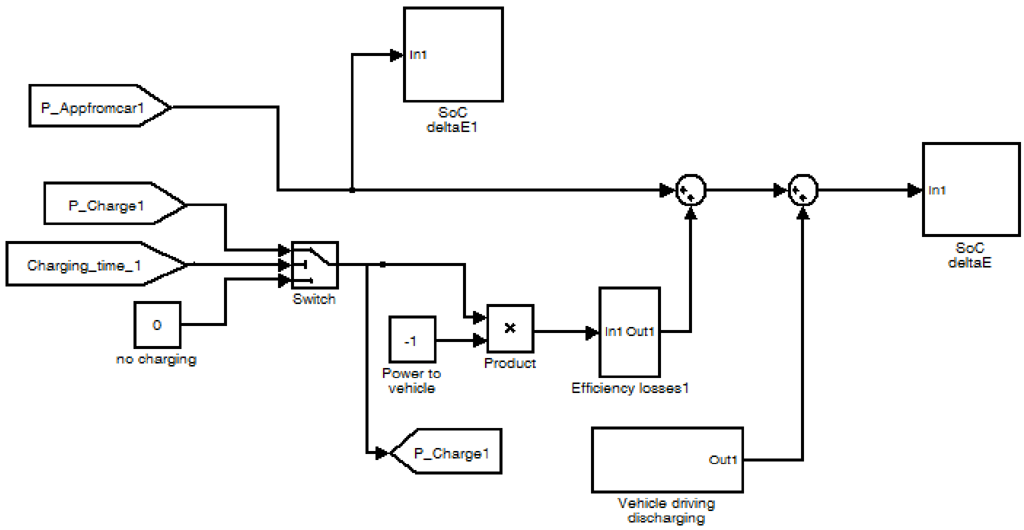

Figure 4.3: Vehicle Subsystem: Simulink model of power flows to and from the vehicle battery.

can be identified as discharge current, voltage limit (discharge end point) and temperature [39]. The first two inputs can be derived given a knowledge of the instantaneous power to/from the battery; the battery temperature must also be input if its effect is of interest.

Battery charging/discharge efficiency

As energy is transferred between different components, a proportion of that energy will be lost to the surroundings; these are efficiency losses. The process of charging and discharging to and from the battery pack has associated efficiency losses. Not all of the energy that is transferred to the battery during charging will be stored in the battery as useful energy. Further, not all of the energy that is stored in the battery pack can be used. These ratios of energy conversion are charging and discharging efficiencies, respectively. Equations 4.2 and 4.3 describe the loss of power through efficiency losses.

The efficiency losses during a charge/discharge cycle are determined by several factors including temperature, charging/discharging rate (rate of transfer of energy). The relationships will vary for each individual battery. To some extent, attempting to simulate battery efficiency losses is futile—every battery is different so each time the model is run different efficiency loss parameters must be input. Therefore, it is important to ensure the simulation of efficiency losses is implemented so it is flexible to incorporate any battery chemistry and is easy to modify in successive simulation runs.

Note that with modern Lithium based batteries the variation of charging efficiency with power input/output is not as pronounced as with older battery chemistries.

Figure 4.4 shows the Simulink model used to simulate efficiency losses. In this case a multiplication by a charging efficiency constant.

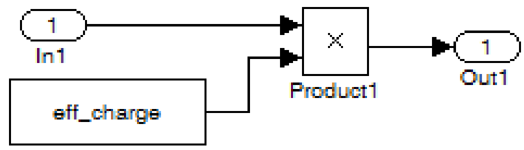

Figure 4.4: The Simulink model used to simulate efficiency losses.

Battery degradation

Energy storage will have a finite lifetime; its ability to store energy will degrade over time. This is an issue that particularly affects batteries.

Battery degradation is different to self-discharge in that the loss from the former is permanent. The capacity of a battery at full charge reduces with time as unwanted chemical reactions or damage to the components occur within. Each charge and discharge cycle is not completely reversible; this gives the effect of a net loss in battery capacity each cycle [40]. In the degraded battery the 100% state of charge is only 80% of its original—this degradation is captured in the term state of health.

The rate of degradation depends upon several factors. Notably, the "depth" of each charge discharge cycle will effect the rate of degradation. A battery can tolerate many more partial discharges than deep discharges. The depth of discharge (DoD) for batteries is the percentage of the capacity that is removed from the battery during a discharge. Many full discharges (100% DoD) will degrade the battery much more quickly than many partial discharges; for example, a lead acid car battery will last only 125-250 deep cycles while it will last 3,000 partial cycles [40]. Lithium based batteries fare better than lead-acid batteries in terms of durability by around a factor of two [41]. Figure 4.5 shows the effect of battery use on lifetime graphically.

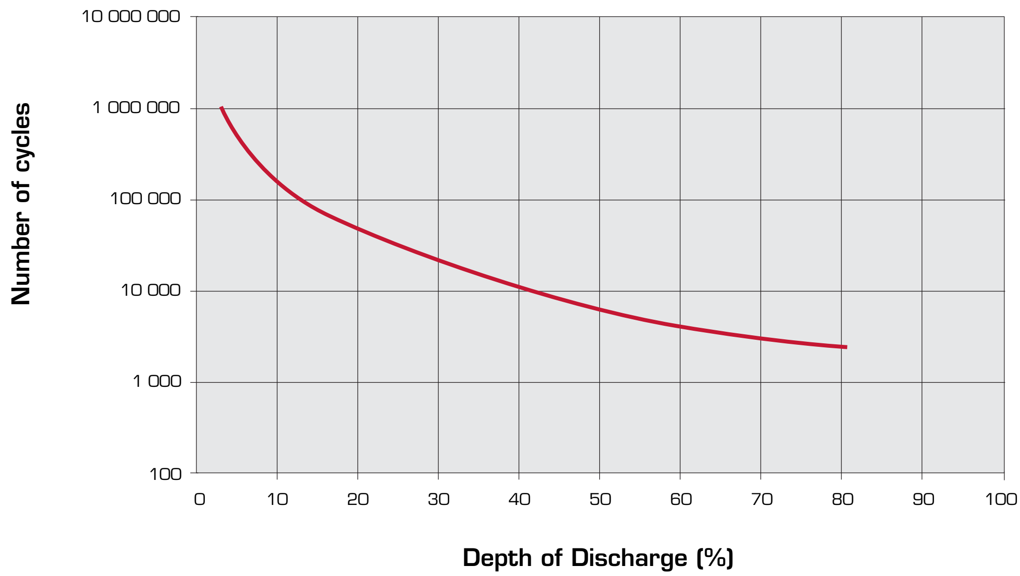

Figure 4.5: Cycle lifetime for Saft Intensium Flex; tested at 25°C; reproduced from Saft marketing literature.

This dependency on the depth of cycles on battery life suggests that, to extend the life of the battery, the battery capacity should exceed the requirements of the application it is designed to fullfil (as with the batteries in conventional vehicles). Battery lifetime management will be a major factor in vehicle-to-grid scenarios.

4.4.2 Household Subsystem

For most vehicle-to-grid applications, the tool must include some simulation of electricity use in nearby buildings and infrastructure. In vehicle-to-home applications the household electricity system and the vehicle are treated as a closed system—the interaction between vehicle storage and the household electrical appliances is the focus of the study.

The physical system consists of a set of electrical appliances that require electrical power. Conventionally, that power is supplied from the electric supplier via a single in feed to the household. Different ways of supplying the required electricity can be envisioned and will alter the physical picture significantly. As such, the generation of electricity will be discussed in a separate section.

The physical grid within a household could be simulated at varying levels of fidelity. The simplest simulation would only consider the mains in-feed to the household. This is simulated as a power in-feed—an array of power values versus time. This functionality is included in the model; it requires an appropriate data set of household power use versus time. Note that the energy usage of the household can also be analysed at various levels of fidelity—notably time-wise. This will be discussed in Section 4.5.

The most detailed model would simulate a comprehensive list of electrical appliances and their interaction with the household mains. All the relevant electrical phenomena—capacitance, impedance etc—could be simulated to give a truly accurate physical picture of the electrical demands of the household.

A physical model somewhere between the two extremes was also implemented. A library of common electrical appliances is provided—each appliance is simulated using a reasonable power-versus-time duty cycle. The demands of each appliance are treated in terms of power; and power is treated as a scalar. While this simulation approach does miss some detailed electrical phenomena, the simulation is kept energy and power based for reasons previously discussed.

Table 4.6 lists the appliances that are included in the model library[††]. By selecting the appliances that are in a given household, the physical grid for that household is simulated. As more households are considered, the physical grid becomes more complex and this approach quickly becomes unfeasible.

Table 4.6: List of household appliances available in model library.

Television	Television receiver box (Sky/Cable)
DVD	PC/laptop
Mobile phone	Clock radio
Lightingvarious types	Space heater
Water heaters	Cooker—oven and hob
Toaster	Microwave
Washing machine	Tumble dryer
Dishwasher	Kettle
Fridge/freezer	Shower

4.4.3 Generation Subsystem

The electricity generation, transmission and distribution system can be viewed (and therefore simulated) at a range of scales. Electricity transmission in the UK

[††]The list is by no means exhaustive; the model library can be expanded if necessary, provided power usage information is available for the appliance.

is overseen by National Grid. Since the focus of this study is vehicle-to-home in particular, the generation, transmission and distribution grid sits outside the vehicle/building systems. It is the effect of vehicle-to-home (and electric vehicles) on these systems that is of interest. A high vehicle-to-home penetration rate will impact the operation of the electric grid up to a national scale, but smaller penetrations of V2H can have an impact on local grids (and local applications of energy storage).

The approach taken to the simulation of the electricity generation system very much depends on the type of generation used:

Fuel Coal, gas, oil fired, nuclear, renewable etc.

Scale Large power plants versus distributed generation.

Location Similar to scale, distributed generation will likely be closer to the vehicle—the physical system is different.

Fuels are treated in one of two different ways: as controllable energy supplies or as intermittent supplies.

Traditional fossil fuel generation—coal, gas, oil—converts chemical energy in these substances to electrical energy (by combustion). Nuclear generation generates electricity via nuclear fission of an appropriate fuel. Fuel cells generate electricity via the oxidisation of hydrogen or other hydrocarbons. Biomass generators generate electricity via combustion or output combustible fuels via chemical reactions. These methods of energy conversion are similar in the sense that the generation of electricity can be controlled to match demand. If more electricity is required then more can be generated, as long as there is sufficient fuel available. This type of generation can be characterised using performance curves. For a given generator, the amount of fuel required to generate electrical power is known. Operational costs and operational carbon emissions can be extrapolated from here. Adding in capital costs and embedded carbon gives a full picture of the electricity used.

Some energy supplies are inherently intermittent; wind turbines and solar panels fall into this category. The amount of power delivered and when it is delivered (and how well this can be predicted) will depend on the natural resource that is used. Solar panels only generate electricity when sufficient light is incident upon them. Wind turbines only generate power when wind blows with sufficient strength and quality. It is important to understand when the generator is supplying power and how much. Performance curves are still useful in the characterisation of intermittent supplies. It is useful to know how much electricity can be generated given different conditions:

- When building a case for commissioning at a site;
- when optimising the design of the site (for example, sizing of generators, wind turbine positioning);
- when assessing operational requirements at a site (for example, assessing the transmission and distribution requirements requires knowledge of the peak generation from the site); and
- when building short-term predictions of power generation from the site.

The scale of the generation being simulated changes the parameters used in simulation. Small-scale or distributed generation is placed close to the load and will generate enough energy for a single household, a community or perhaps a small commercial premises. Large-scale or centralised generation is connected to the load via a grid system and will generate energy for a large number of customers. Distributed generation benefits from the lack of a need for transmission infrastructure and the associated transmission losses. The simulation of distributed generation amounts to simulating the parameters associated solely with the generator. Large-scale generation requires transmission and distribution infrastructure to deliver power to the load. From a purely energy delivery perspective, the simulation of large-scale generation must include transmission and distribution and the losses incurred. Large-scale generation benefits from economies of scale when compared to small-scale generation.

The UK National Grid is fed by many large-scale and small-scale generators using different fuels. The detail of how the electricity drawn from the grid at any one time is determined by the mix of generation at that time. In principle, the grid mix at any one time can be determined and the exact origins of the electricity dawn from the grid can be determined. In practice, average grid mixes are used to characterise grid electricity. The power demanded from the grid over a period of time can be an output from the model. This output can feasibly be used to study details of cost, greenhouse gas emissions etc based on assumptions about the grid mix.

4.4.4 V2H Management Subsystem

There are two separate aspects of control within the model: Generation requirements and vehicle-to-home status.

The generation requirements depend on the application being studied. The simulation tool must be flexible to different V2H applications. This was achieved by inputting the generation-side requirements as an array. Figure 4.6 shows the generation control section of the Simulink model of the distributed generation case study, as an example.

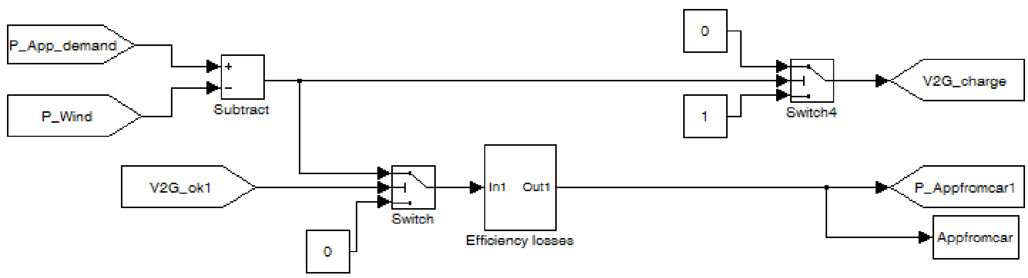

Figure 4.6: Screenshot of Simulink model; control of generation requirements.

In this case study, the generation requires support from the vehicle battery to supply household demand when generation is insufficient and to accept excess generation. Ultimately, the required power from the vehicle is the difference between household demand and generation. This difference is taken by the model. The model then decides if the required demand will be met, based on the input *V2G_ok*—the vehicle-to-home status. Inputting generation requirements in this way is very flexible. The time varying requirement can be calculated based on the V2H application. For example, if the generation requirement is that the V2H system demands a constant power supply from the grid then the power required from the vehicle equals the difference between the household demand and the constant demand. The generation requirements might be determined by indirect means, for example, by variable pricing tariffs.

Figure 4.10 shows part of the Simulink model that takes vehicle availability and vehicle charging time and SoC levels and constraints as inputs and outputs if vehicle-to-home is possible or not.

The inputs to the *V2G_ok* decision are: *Availability*, *Chargingtime*, *SoC*, *SoC_min*, *SoC_max* and *V2G_charge* (Note that *Availability*, *Chargingtime* and

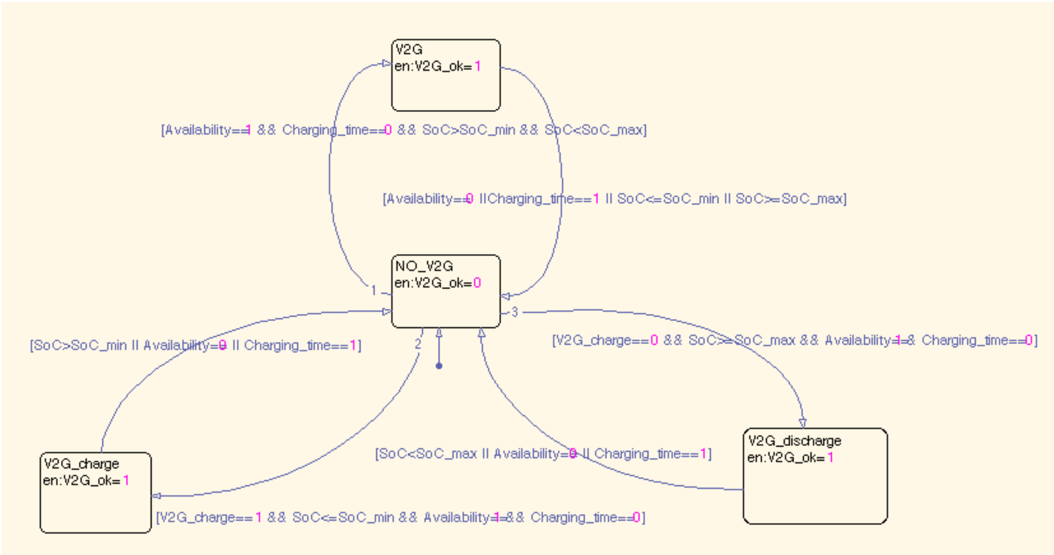

Figure 4.7: Screenshot of Stateflow model; V2G ok variable.

SoC depend on how the usage of the vehicle—this is discussed in Section 4.5). As can be seen in Figure 4.10 there are four potential states based on the value of these inputs. The default state is to deny vehicle-to-home operation—no_V2G. If the vehicle is available (present at the household), does not require charging, and the SoC sits between the minimum and maximum then entry to the V2G state is satisfied and Stateflow outputs $V2G\_ok = 1$.

The two states $V2G\_charge$ and $V2G\_discharge$ determine V2G behaviour at the limits of battery SoC. If SoC is below the desired minimum, then the vehicle battery should not be used to supply the household, but the vehicle battery can accept charge. The $V2G\_charge$ input informs Stateflow if charging vehicle-to-home or discharging vehicle-to-home is required. And, if charging V2H is required then entry to state $V2G\_charge$ is allowed and $V2G\_ok = 1$. The converse is true for if the battery SoC is above the set maximum.

If, at any time, the vehicle ceases to be available or the vehicle must charge, Stateflow reverts back to no_V2G and $V2G\_ok = 0$ is output.

The combination of the Power demanded from the vehicle for the generation and the status of the $V2G\_ok$ parameter are used to calculate $PAppfromcar$. Figure 4.6 shows the calculation and control of $PAppfromcar$ via a switch controlled by $V2G\_ok$. The change in energy in the vehicle battery is then calculated in the Vehicle Subsystem and the simulation proceeds to the next timestep.

4.5 User Behaviour

The tool must allow for the identification of inputs and constraints that are determined by the behaviour of actors in the vehicle-to-home system. The application of the use case methodology ensures that the tool has a user focus. In this Section, the modelling capability required to consider user behaviour is outlined.

4.5.1 Vehicle

The time varying parameters that must be input to the vehicle system are summarised in Table 4.7.

Table 4.7: Summary of the time parameters for a vehicle.

Parameter	Summary description
Vehicle availability	For a vehicle to be capable of providing vehicle-to-grid, it must be plugged into the grid
Vehicle use	The timing of driving and the impact of battery SoC
Future use	Some element of how the vehicle will be used in the future

Vehicle Availability

The required input to the model is simply if the vehicle is available and plugged in, or not. The solution was to have a time varying feed, in the form of an array, fed into Simulink. Figure 4.8 shows a screenshot of an array displayed in Matlab. In Figure 4.8, the two columns correspond to time and availability—they are marked accordingly.

In a Matlab array, the variable being input to Simulink must have an associated time series. This time series will correspond to the running of the simulation. By using an array, the vehicle availability input is flexible to different data sets. For example, in the array presented in Figure 4.8, the simulation was set to run over a single day, and 288 time steps—each time step corresponds to 5 minutes. Using the array input, it is feasible to input data recorded (or created) over any time step resolution.

While the example in Figure 4.8 is a Matlab array, any data stored in a similar format can be imported to Matlab. Importing data from Excel, for example, is a straightforward process.

Availability <288x2 double>

	1	2	3	4	5
78	77	1			
79	78	1			
80	79	1			
81	80	1			
82	81	1			
83	82	1			
84	83	1			
85	84	1			
86	85	1			
87	86	0			
88	87	0			
89	88	0			
90	89	0			
91	90	0			
92	91	0			

Figure 4.8: Availability array fed from Matlab into Simulink

Vehicle Use

The primary use of a vehicle is driving—the model must be capable of simulating use through driving and the impact this has on the battery. Vehicle use is of course linked to vehicle availability in the sense that if the vehicle is driving it is not connected to the grid. Following this logic, the vehicle driving use was simulated using availability as a basis. That is, the model assumes that when the vehicle is not available ($Availability = 0$), it is driving. This assumption oversimplifies the issue, for example, the vehicle may be unavailable simply because it is not plugged into the grid. Such circumstances can still be captured by correctly simulating the power demanded from the battery during the $Availability = 0$ period. In the case of an idle but unplugged vehicle, the energy loss should equal the battery self-discharge over that period.

The battery discharging that occurs through vehicle use could be simulated to different levels of accuracy. The basic requirement in journey modelling for vehicle-to-grid is the journey start time and the journey end time. Additionally, the model must be able to estimate the amount of energy used from the battery for driving. This could be achieved in several ways, for example:

- Data from real journeys in electric vehicles could be recorded, with initial and final battery state of charge being measured.
- Journeys in non-electric vehicles could be measured and from this data the

battery energy use can be simulated in detail. The required measurements include: vehicle speed versus, gradient and vehicle parameters like driving efficiency. The hybrid electric vehicles group at Warwick University have developed such a simulation tool. Warwick's tool is called WARPSTAR; similar simulation tools exist.

- Less precise estimation techniques can be used. For example, if the distance of the journey is known and the driving efficiency is known, the energy required for the journey can be estimated.

In this tool, vehicle driving is simulated in a 'black-box' fashion. The tool is not capable of estimating a power draw based on the details of a vehicle journey; there are other simulation tools that are capable of this simulation task. The required input is a power draw caused by driving versus time.

One main aim in developing the model is flexibility; ideally the model should be flexible enough to accept any of these methods. The chosen simulation approach allows a power versus time profile to be calculated using any of the aforementioned methods and input to the model in the same way.

Vehicle driving is subject to energy losses. In an electric vehicle, the energy stored in the vehicle battery is converting into kinetic energy of the driving. Unfortunately, some of this energy is lost in the conversion process. The fraction of stored energy that is successfully converted to kinetic energy of driving depends on the efficiency of conversion.

Efficiency losses in driving could be simulated in various ways. A detailed driving simulation tool would estimate drivetrain efficiency losses based on vehicle operating conditions. This simulation tool is concerned with simulating the interaction of the vehicle energy storage and the grid. The only parameter of interest is the battery condition before a journey and after that journey. The details of how the battery state of charge varies due to driving usage is of no concern to the model[‡‡]. Therefore, driving efficiency losses are incorporated in the driving inputs. Driving efficiency is not calculated—and efficiency losses applied—by the tool based on the driving inputs.

[‡‡]It may become a concern if some of the finer details are considered. Or if driving behaviour is considered alongside vehicle-to-grid.

Vehicle Charging

Vehicle usage requires energy from the battery. This energy must be replaced for electric vehicle use to be sustainable over a long period of time. This replacement of energy must take a priority over using the vehicle for vehicle-to-home. However, some vehicle-to-grid applications (using the vehicle to reduce the frequency of the grid, for example) will charge the vehicle by necessity. It is only true to say that, over a chosen period of time, the final battery state of charge must be the same as the initial state of charge, that is, the energy taken from the vehicle for the purpose of driving and for vehicle-to-grid must be replaced. The length of this time period depends on the usage of the vehicle.

The model includes a calculation of the required charging time (and hence the $Chargingtime$ input). A target SoC is input along with the time by which this target must be met. Given the power input of the vehicle charger, the model calculates the required starting time and ending time of vehicle charging. An $Chargingtime$ array is created (or input by the model operator). Similar to the availability array, the charging time array consists of ones and zeros. Ones denoting that the vehicle must charge.

4.5.2 Surrounding electrical infrastructure

To emphasise the point: the difference between this simulation and work carried out previously is the use of time series data rather than averages—this is true for the simulation of building electricity use. The tool must be capable of accepting or generating time-varying electricity demand data.

As with the simulation of the vehicle physical system, the household electricity usage can be simulated using different approaches and with varying levels of detail.

Data Generation

An electricity demand profile can be created by simulating the usage of all the electrical appliances in a building (or group of buildings)—for example those in Table 4.6—and summing the individual demands to create a total demand profile. The required inputs are: the details of how each appliance uses electrical power in a given duty cycle; the frequency duration of usage; and some estimate of exactly when an appliance is used. Simulation of the first input is straightforward. Most electrical appliances have a simple power consumption profile—a lightbulb, essentially, draws a constant power when it is running. More complicated appliances, washing machines for example, have a more variable power draw over the duty cycle, but the power draw can be simulated for a given cycle. The second two inputs are based on human behaviour; the inputs will have some degree of statistical variation.

An electrical load profile can be created using bottom-up models. Bottom-up models simulate the usage of individual electrical appliances and sum the loads from each to give a load for a building. For example, Walker and Pokoski [42]generate residential electricity load models based on the statistical prediction of building occupancy and statistical models of electrical appliance usage—how often a given electrical appliance is used in a household [42].

The vehicle-to-home tool can generate an electricity usage profile from individual electrical appliances, but it requires significant human guidance. The model contains no statistical capability like the models described above. If the users wants to build an electricity demand profile up from basic appliances then the model allows this, but the user must input the time and duration of use of each appliance. Further, the user may have to modify or define some extra electrical appliances. The model contains a catalogue of common appliances that can be used, but the catalogue is not exhaustive.

In further iterations of the model, it would be possible to include an automatic household demand generator based on a chosen statistical method. Indeed, one of the statistical methods described above could be implemented. However, the development of such models is an entire field of research in itself. The inclusion of a statistical model is outside the scope of the doctorate. Of course, it is sensible to build a tool with sufficient flexibility that it can accept the outputs from such usage generating models.

Data Input

The household demand profile generation methods require data inputs, for example, household occupancy data. Any of these methods demands that the user acquire detailed data concerning household behaviour. Given this fact, it seemed sensible that the option to input electricity usage directly was an option available to the model user. Unfortunately, it is difficult to find electricity use data from a single household or from a small number of buildings. Generally, the electricity supplier measures the electricity usage in a household monthly, quarterly or less frequently. Therefore, data detailing household electricity use in short time intervals (for example minute by minute usage) is not widespread. Detailed use data does exist, but it is generally the result of a specific observational experiment, not from standard bill taking by the electricity suppliers.

If a researcher is interested in obtaining a sample of electricity use data collected more frequently that monthly, then they must find data that has been collected by another researcher and is in the public domain. Such data does exist and will be used in demonstrations later in this submission. Alternatively, the researcher could create an experiment to collect detailed data. Recording electricity demand data is straightforward in principle. The vast majority of households have an electricity meter and, if it is assumed that this meter is reasonably accurate, the researcher just needs to record the meter reading at chosen intervals.

Recent developments have made this process more straightforward. Basic "smart meters" have become more common in recent years, several electricity suppliers offer meters to customers and the UK Department of Energy and Climate Change smart meter rollout promises a smart meter in most UK households by 2019. Such meters can be connected to the incoming mains electricity and will display an instantaneous power demand for the household. Recording this instantaneous power demand will allow the researcher to construct a power profile over a period of time. While manual observations are a simple way of recording household electricity use, the method is of course prone to errors.

Automatic observations are not prone to human error. Accurate electric meters that record usage can be purchased and fitted, but at a financial cost. In the context of this doctorate, the purchase of one—even several—accurate electric meters was a possibility. But practically, the amount of data that could be collected in a limited timescale would be limiting. More crucially, the variation in the data would be limited. Ideally, one would collect electricity usage data from a range of households over a long period so that seasonal variation could be observed. A study that would be so intrusive to such a large number of people, for such a sustained period and at a high financial cost was deemed impractical for a single EngD project. Especially considering the aforementioned fact that detailed data has been collected in previous studies.

Generally, electricity use data is displayed as a constant power draw over a fixed repeated time period (for example, five minute interval data). This type of data lends naturally to a Matlab array. Similar to the vehicle-based inputs, the electricity demand data for a building was input in the form of a Matlab array. This solution has the same benefits as with the vehicle inputs: it is flexible. The input of electricity usage data from any data source only requires that the data is converted to a Matlab array and combined with a time stamp.

Figure 4.9 shows the household power demand input as a Matlab array.

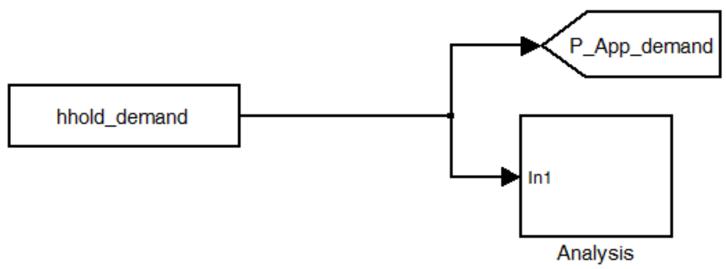

Figure 4.9: Simulink model of household power demand array.

4.6 Model Outputs

Figure shows the generic subsystem used to calculate some useful outputs from the model. The power flow measured at the relevant point in the model of the V2H system is input. The analysis subsystem is used to calculate total energy, peak power, average power and load factor (the ratio of average power and peak power) over the duration of a simulation run.

Equations 4.4, 4.5 and 4.6 describe the calculation of output parameters in Simulink.

$$E_{total} = \int P.dt \tag{4.4}$$

where E_{total} is total energy transferred and $P.dt$ is the power transferred over a given time.

$$P_{average} = \frac{E_{total}}{stepsinperiod} \tag{4.5}$$

where $P_{average}$ is the average power over a time period, E_{total} is the total energy as defined in Equation 4.4 and the denominator *stepsinperiod* is the number of steps in the chosen time period.

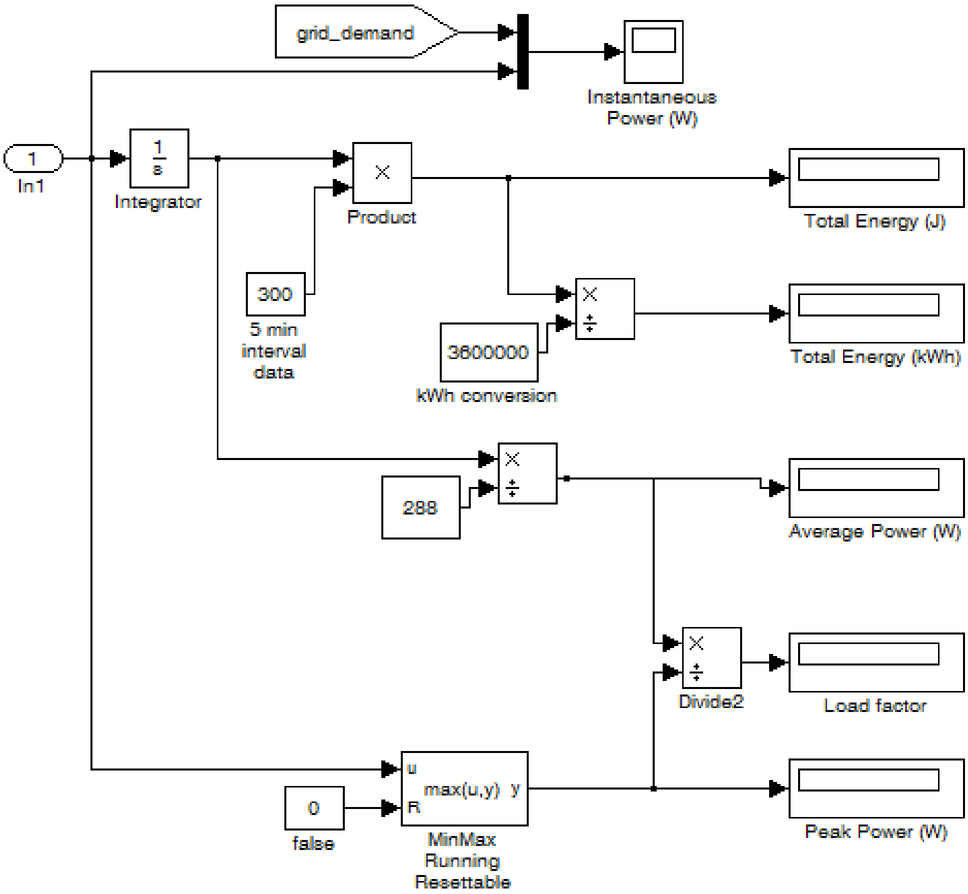

Figure 4.10: Generic analysis subsystem used to calculate various parameters given power input.

$$LF = \frac{P_{average}}{P_{peak}} \tag{4.6}$$

where LF is the load factor, $P_{average}$ is the average power as calculated in Equation 4.5 and P_{peak} is the peak power observed in the chosen time period.

5

Case Study: "Back-up" Supply

In this Chapter, a simple case study is used to illustrate the operation of the model: The use of the electric vehicle battery to provide electricity to the household in emergency situations; "back-up power supply". The simulation of back-up storage is important. If the grid power supply to a household fails for whatever reason, the occupier will benefit from having an alternative power source available. Consumers sometimes choose to use diesel back-up generators to supply power during grid failures. Unfortunately, accidents sometimes occur where the emissions from the diesel generator enter the house and the occupier is suffocated or poisoned. The US Consumer Product Safety Commission reports that "at least 95 generator related CO (Carbon Monoxide) poisoning deaths" in the US in 2005 alone [43]. Replacing diesel generators with electric vehicle storage is a potential solution to this problem.

Back-up generation is a simplified example of vehicle-to-home. It is assumed that, during the emergency usage the vehicle will not be used for driving. The case study is based on an emergency situation and the vehicle will not be used as the primary transport. The range buffer will remain in place as an an emergency travel function. Since vehicle availability or driving need is no longer an issue, the vehicle-to-home simulation is essentially a stationary storage one.

This case study will demonstrate the operation of the tool. It will demonstrate some of the functionality of the tool:

- The capability to handle granular household electricity demand data; and
- the capability to simulate some aspects of an electric vehicle used for storage.

This case study will be used to explore sensitivity to the variation of input parameters. Given that this case study is focussed on the household energy usage part of the the model, the household energy use data that is used in all three case studies will be introduced and discussed here.

5.1 Use Case

The use case narrative in this case study is as follows: "The customer (vehicle operator) wishes to use the battery of their electric vehicle to supply their household appliances at a time that the grid supply has failed."

The system actors that are relevant in this case study are a subset of those outlined in Table 4.4. This case study will demonstrate the model operation in simplified circumstances, that is, without the complexity of vehicle usage. Figure 5.1 is a modified version of Figure 4.1; the boxes highlighted in red are the systems that are relevant in this case study.

The Vehicle Inputs functionality of the tool are only partially used in this case study. The vehicle is not mobile, so constraints associated with vehicle usage are not relevant. The physical storage system is still relevant, so functionality associated with vehicle storage is included. Building Inputs are required—the vehicle operator wishes to power load from the vehicle so load must be known. Generation inputs are, by definition, not required since the generation supply has failed. Some element of control is required, but this is limited to matching the power flow from the battery to the household load, and respecting the range buffer. Outputs will be vehicle related only, again, the generation side is not relevant. Insights will be gained into the use of electric vehicle storage as back-up generation.

Further application of the use case methodology to describe the case study scenario and to explore the interactions between actors allows the identification of key inputs, processes and outputs that are important in this case study. Tables 5.1 and 5.2 describe the high-level case-study scenario and the interactions between actors, respectively.

Table 5.2 presents the interactions between vehicle and customer energy management system in some detail*. In this case study, the key interactions are:

*This detail is left in after its identification in the EPRI use case (Table 4.3). The detail of interactions between ICT systems on the vehicle is not the focus of this project and certainly not the focus of the V2H tool. However, the inclusion of such detail does not detract from the discussion—this detail must be considered if a physical V2H system is being built.

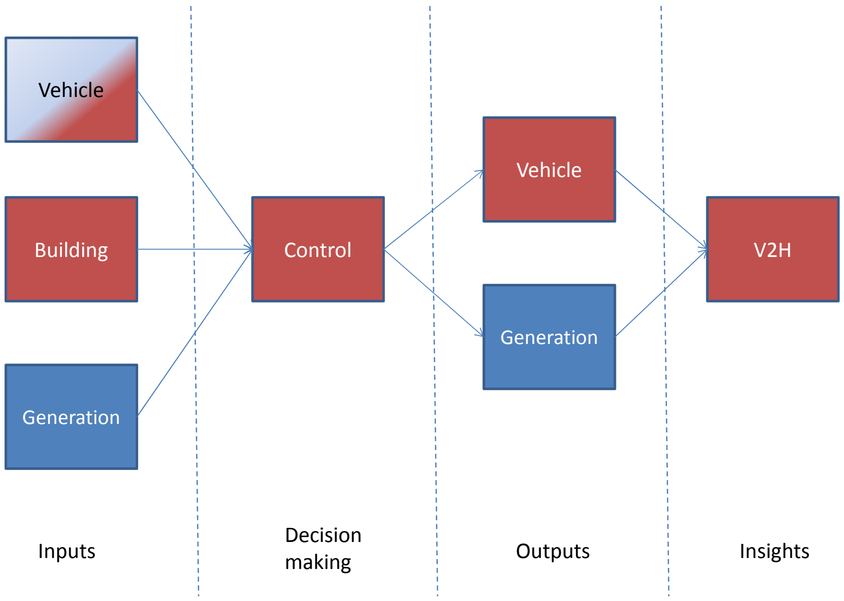

Figure 5.1: Conceptual diagram of the simulation tool; highlighted to show relevant systems in back-up generation case study.

Table 5.1: High-level description of vehicle-to-home back-up generation scenario.

Triggering event	Primary actor	Pre condition	Post condition
Grid supply fails	Customer	Customer has electric vehicle and a charger, control and energy management system that interfaces with EV	Customer has successfully operated their EV in providing back-up power to household appliances

- Electricity supply to household fails;
- customer instructs vehicle to supply household load;
- energy management system and EV exchange vehicle ad household parameters and decide whether or not to supply household load depending on these parameters; and
- customer disconnects vehicle or instructs that back-up is no longer required.

It follows that the key inputs are:

- Household demand over the period of grid failure;
- vehicle parameters that determine the decision to supply/not supply household load;

Table 5.2: Step-by-step interactions between actors within a vehicle-to-home system in back-up generation scenario.

Step	Actor	Description of step
1	Supplier	Electricity supply to household fails
2	Customer	Customer connects EV to charging device and instructs vehicle to supply back-up power to household
3	EV	EV senses power to on-board charging unit and begins charging or discharging based on operator selected preferences
4	EV	EV binds with customer energy management system
5	Customer energy management system (CEMS)	CEMS executes program that controls EV discharging to supply household load
6	Customer energy management system	CEMS and EV exchange information and energy storage parameters (ie. Storage capacity, state-of-charge, charging rate, discharging rate etc.)
7	Customer energy management system	CEMS sends control signals to EV requesting discharging to supply household load
8	EV	EV processes control messages sent from CEMS and executes them after verifying request against current vehicle parameters and ensuring sufficient energy stored to supply household load
9	EV	EV sends message to CEMS confirming control message and EV status
10	EV	Customer disconnect EV from energy portal or instructs EV that back-up is no longer required
11	Customer energy management system	CEMS senses session has ended and terminates program that controls EV discharging to supply household load

  - The battery state-of-charge—there must be sufficient energy to supply the load and preserve the range buffer; and
  - charging/discharging rate—to determine the change in SoC and inform on efficiency, degradation etc.

- Whether or not the back-up is required.

Based on these inputs and the variation of the parameters as back-up power is supplied, the V2H tool control system will decide if the provision of back-up power can continue. Ultimately, when the stored energy is spent, the back-up supply will discontinue. The key issue in this case study is *for how long will the EV storage be able to supply the household?*

5.2 Household Electricity Demand

Electricity demand data, recorded over short time intervals is difficult to obtain[†]. Typically, a household electricity meter is read every few months—this is an ex-

[†]Though, as noted in Section 4.5.2, the proposed rollout of smart meters may make detailed household demand data more commonly available.

traordinarily long time interval and is completely useless for the modelling approach employed here. UK National Grid demand data is recorded at 30 min time intervals (or settlement periods); which 30 mins is a more appropriate time interval, the data is for the national scale, and so is also not useful for the V2H modelling approach taken here. Simply scaling down the national electricity demand to a single household level (approximated by dividing the national domestic demand by the number of households) will not give an accurate single household demand. When multiple demands are added together the peaks in demand are smoothed. This can be observed by comparing the national electricity demand with that of a single household—the latter is more "peaky".

A source for single household, short time interval data was found in Annex 42 of the International Energy Agency's Energy Conservation in Buildings and Community Systems Programme [1]. As part of the Programme, researchers installed measuring equipment in 69 UK houses and measured the electricity consumption over 5 minute intervals. 5 minute interval data is sufficiently granular to register large peaks. For example, an electric shower is a relatively power hungry household appliance. It is feasible that a person spends over 5 minutes in the shower, so the power consumption of the shower should be accurately reflected in 5 minute data. This is not true for all loads, for example a kettle does not take 5 minutes to boil, so its peak power consumption is diluted even over a 5 minute interval. Shorter interval data would be superior, but was not found.

The Annex 42 Programme makes the collected data from three different households publicly available; described by the Annex 42 researchers as high, medium and low demand households. Some features of the three households are summarised in Table 5.3. The Annex 42 researchers judged these three houses to be "typical" of high, medium and low energy demand households in the UK.

Table 5.3: Annex 42 Household Electricity Load Data; Household Profiles.

Description	Location	Annual Consumption (kWh)	Year	Number of Occupants
High	Llanelli, UK	8,387	2003	6
Medium	Newcastle, UK	3,028	2005	3
Low	Newcastle, UK	1,155	2005	1

Figure 5.2 shows the electricity demand from the High demand household from midnight of 6th January 2003 to midnight of 13th January 2003. This is one week from Monday through to Sunday. Figure 5.3 shows the Medium demand

household from midnight of 3rd January 2005 to midnight of 10th January 2005; again one week from Monday through to Sunday. Figure 5.4 shows the Low demand household for the same week as the high demand one.

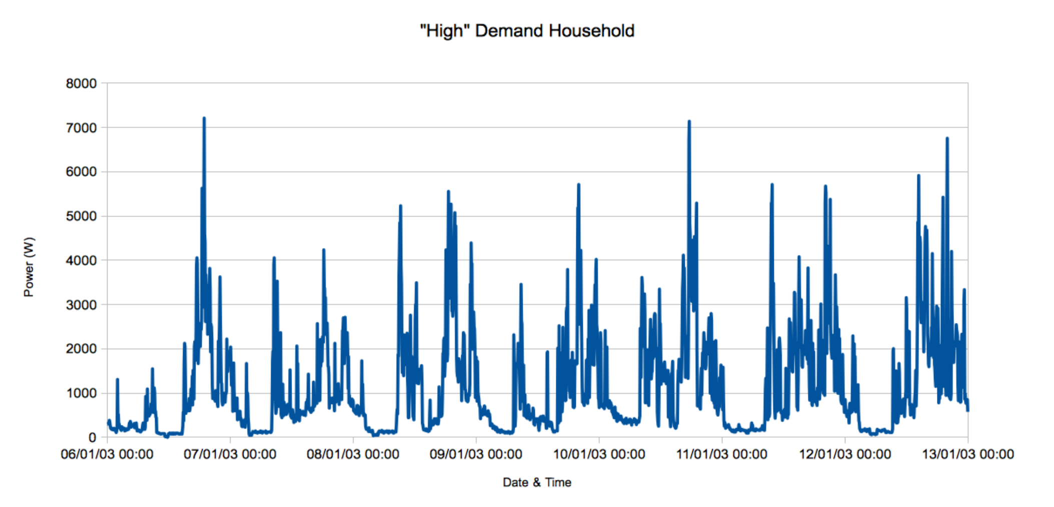

Figure 5.2: High household electricity demand over one week.

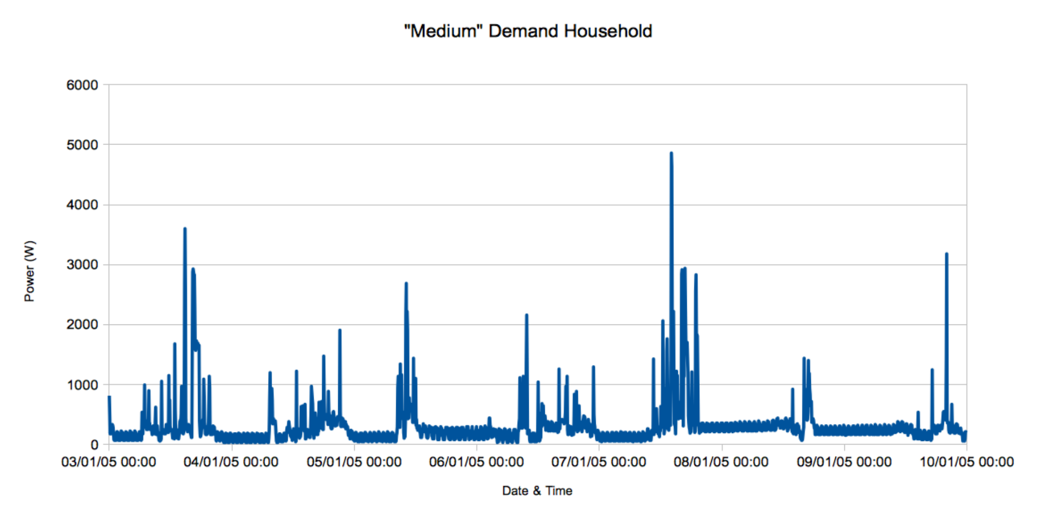

Figure 5.3: Medium household electricity demand over one week.

5.3 Model Setup

The model was run with each of the three household demand profiles and the vehicle parameters as shown in Table 5.4.

The Nissan Leaf has a battery capacity of 24 kWh, this is therefore a sensible initial choice of battery capacity. Assuming a 100% initial battery SoC is perhaps unfair, especially if the vehicle was driven at a short time before the grid failure;

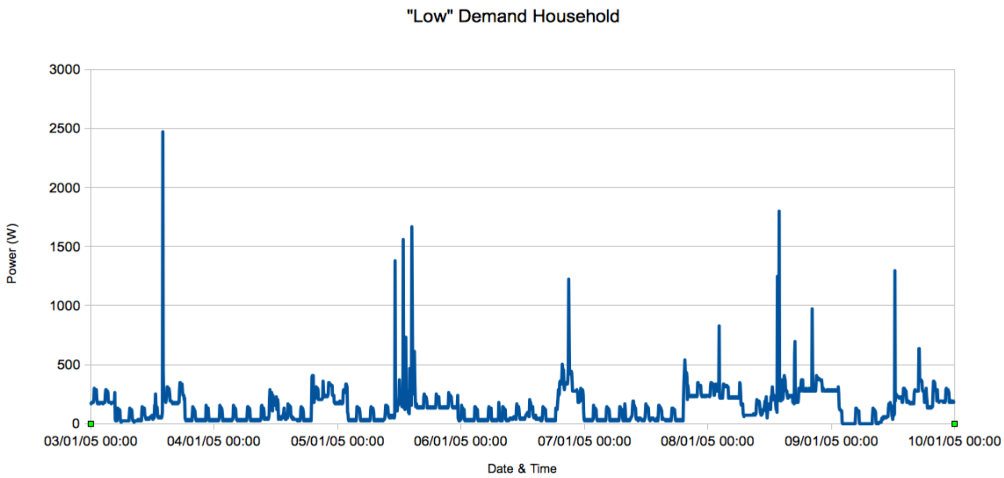

Figure 5.4: Low household electricity demand over one week.

Table 5.4: Vehicle Parameters for Back-up Generation First Experiment.

Parameter	Value
Battery Capacity	24 kWh
Initial SoC	100%
Range Buffer	15 miles
Charging Efficiency	90%
Discharge Efficiency	90%

reducing this initial SoC is similar to reducing the battery capacity parameter value—this is explored in the next Section. A range buffer of 15 miles should be sufficient for emergency trips. For a 24 KWh battery and a vehicle with a 110 mile range on the NEDC cycle, a 15 mile range buffer is approximately 3kWh remaining. This is an oversimplification, given the non-linearity of battery energy storage and the variable nature of driver behaviour, but it is a estimate of range buffer to demonstrate tool functionality. Both charging and discharging efficiency were set at 90%; the sensitivity to this parameter is explored in Section 5.5.

The inputs to the Stateflow Control system are simplified in the case of back-up generation. Figure 5.5 shows the inputs. Availability is input as a constant rather than as an variable array—the vehicle is always present. Charging time is set to zero, since the vehicle will not be charging while it is providing back-up generation; given that the case study is an emergency situation, it is not necessary to establish charging time to meet a target SoC. Maximum, minimum and initial Battery SoC values are input as constants. Current SoC is input as a feedback in from the vehicle system.

Figure 5.6 shows the battery State of Charge for the three—high, medium

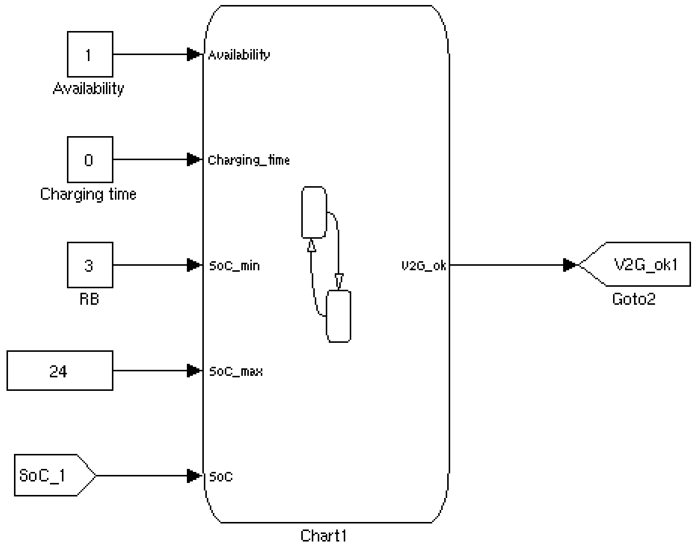

Figure 5.5: Back-up generation Stateflow control inputs.

and low demand—households. In all three cases, the household draws power from the vehicle battery to run electrical appliances until the SoC falls to the range buffer (3 kWh). It is clear from Figure 5.6 that the battery storage is used more quickly when supplying the high demand household compared to supplying the medium household and in turn supplying the low household. The vehicle battery can supply the high demand household for approximately 22 hours; the medium demand household is supplied for two and a half days; the low demand household is supplied for almost six full days. This is to be expected, given the relative energy demands of the three households.

5.4 Battery Capacity

This simple case study was used to demonstrate the variation of battery capacity as a tool input.

Back-up demand with five battery capacities were simulated: 12, 18, 24, 30 and 36 kWh. The largest and smallest capacities being 50% greater than and 50% less than the capacity of a Nissan leaf, respectively. The medium demand household data used in the previous Section was used with all three battery capacity values; a fixed point of reference is required and the experiment of this Section is testing a different variable to that of the previous Section. The same initial SoC, range buffer

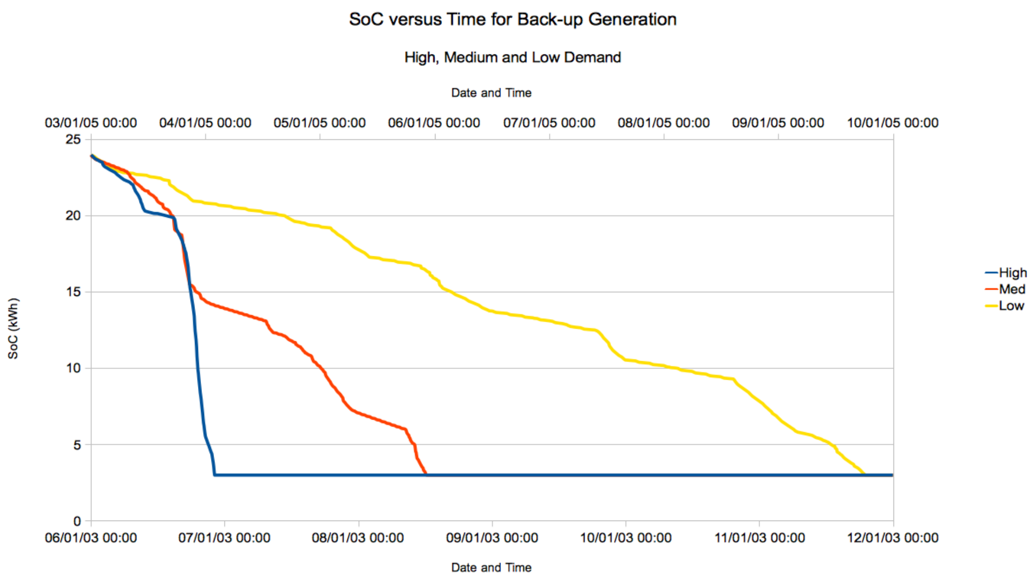

Figure 5.6: Back-up generation case study; Battery SoC versus Time—High, Medium and Low demand household.

and efficiencies were used as in the previous Section.

Figure 5.7 shows the SoC versus time as the vehicle supplies power to the medium demand household, for the five different battery capacities. The five different batteries start at different levels, but fall following the same pattern (since they supply the same load profile). Again, all the vehicles stop supplying power when they reach the minimum defined SoC—the range buffer.

Figure 5.8 shows the battery capacity versus the amount of time for which the household can be supplied with energy. The graph has a trend that is close to linear; any deviation from the straight line is observed because electricity consumption is not constant. The deviation of different capacity batteries from the straight line fit to the data in Figure 5.8 will vary with different demand profiles.

5.5 Efficiency

Likewise, the variation of efficiency can be explored. For this experiment the medium demand household will again be used; the 24 kWh storage capacity will still be used; initial SoC will be 100% and minimum SoC will be 3 kWh. Five different discharging efficiencies will be used: 75%, 80%, 85%, 90% and 95%. As outlined in Section 4.4.1, battery charging and discharging efficiency are dependent on several factors. Efficiencies are therefore usually given as approximations. Battery

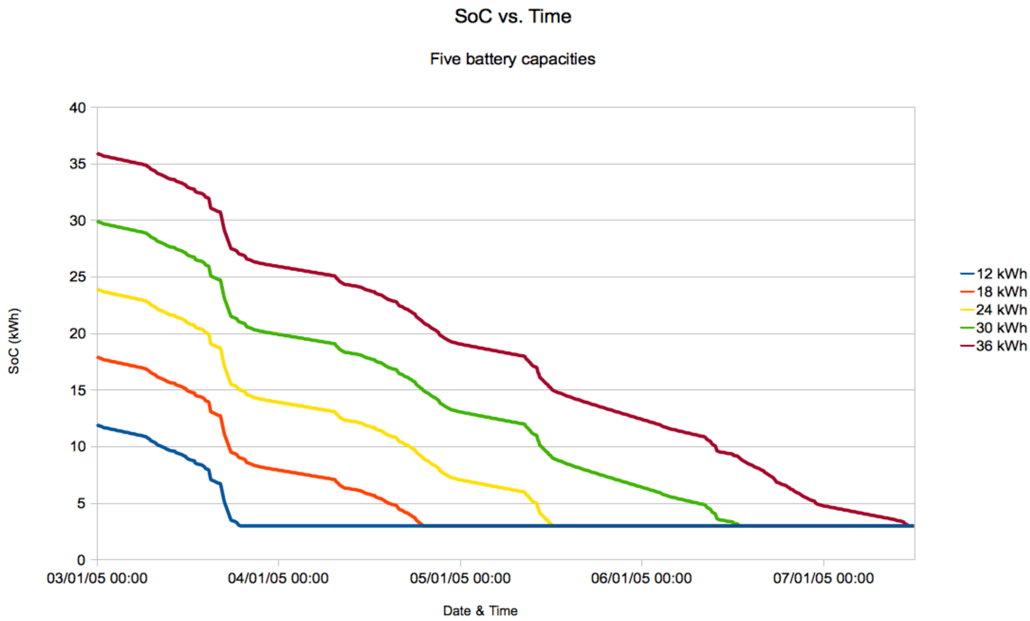

Figure 5.7: Back-up generation case study; Battery SoC versus time—Five different capacity batteries.

manufacturer marketing literature claims energy charging efficiencies in excess of 95%, but discussions with industry experts tends to arrive at 85% to 90% efficiency estimates. Using the range from 75% to 95% errs on the side of caution, as lower efficiencies are bad for vehicle-to-home. Only discharge rate is of interest here: The vehicle is being used as a power supply, so no battery charging takes place.

Figure 5.9 shows the SoC variation with time for the five different discharge efficiency values. The battery SoC is initially the same in all five cases. The SoC falls more quickly with lower efficiency batteries, since more energy is wasted in these cases. The difference in supply duration between the highest efficiency and lowest efficiency battery is 12 hours and 40 minutes. Given that the shortest duration of supply is two days, a twelve hour difference is significant.

5.6 Discussion

The results suggest the importance of judging the feasibility of vehicle-to-home applications on a case-by-case basis, using data from an individual household. It is intuitively obvious that a household with higher energy consumption will expend the vehicle battery more quickly than one with lower consumption. But this has a great impact on the viability of an electric vehicle as a back-up generator. In

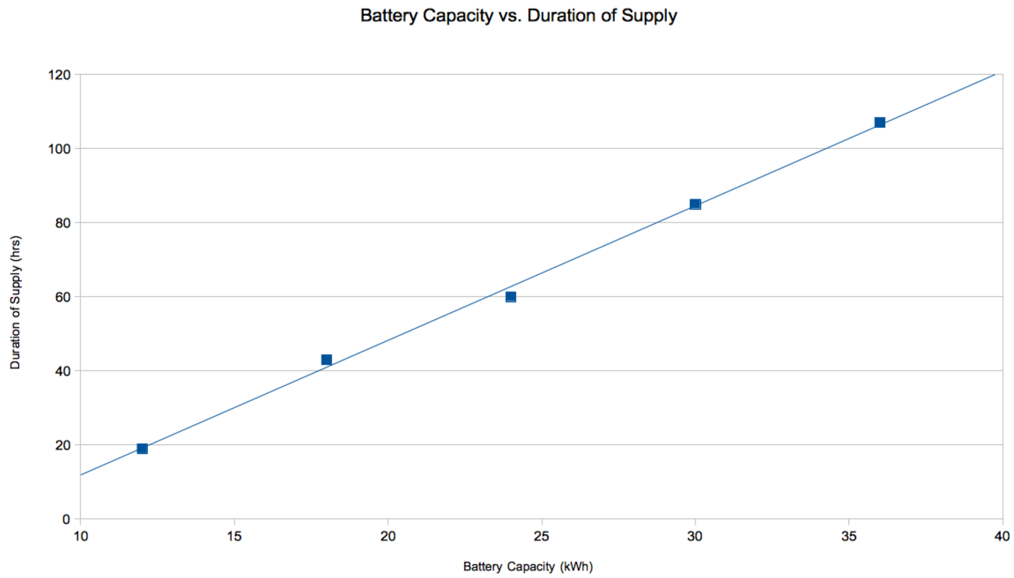

Figure 5.8: Back-up generation case study; Battery capacity versus duration of supply to household.

the high consumption case, the vehicle could only provide back-up generation for a short-term grid failure. Vehicle-to-home for back-up generation is more useful in the lower consumption household. Providing an alternative electricity supply for almost five days, even at the expense of mobility, could prove useful in grid failures caused by infrastructure issues (storms, physical infrastructure failures etc.) This amount of storage could prove particularly useful in rural/off grid areas, where the grid supply may be less reliable.

It seems plausible that if the vehicle is being used in an emergency then only essential electrical appliances will actually be used and the energy demand from the vehicle will be lower than the "normal use" examples illustrated here. This case study can therefore be viewed as a worst case scenario for the household demand data used.

Lastly, if the use of an electric vehicle for back-up generation in place of a diesel generator can avoid a fatal incident, then the application is worth exploring.

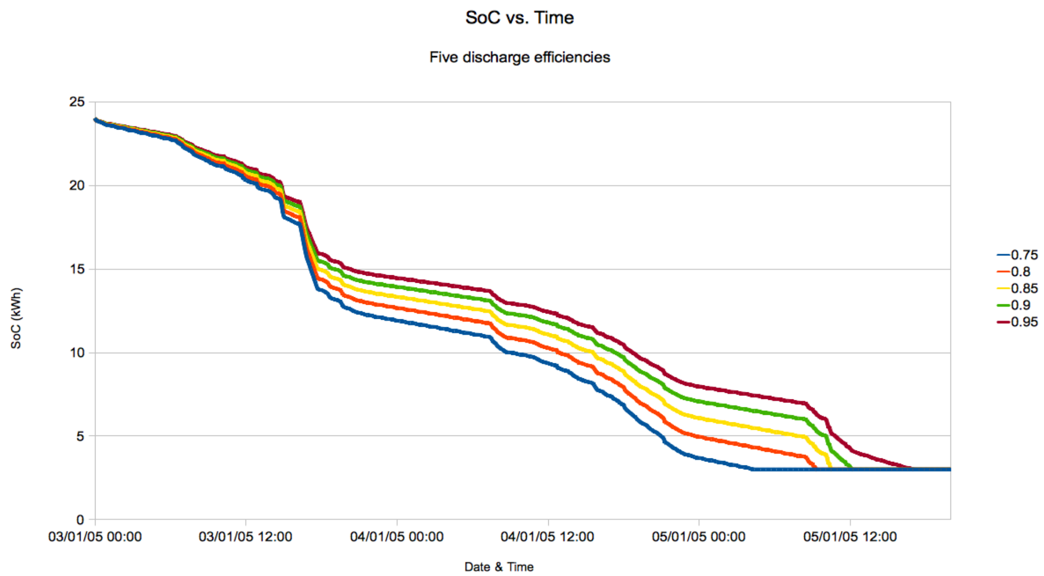

Figure 5.9: Back-up generation case study; SoC versus time—five different battery efficiencies.

6

Case Study: Distributed Renewable Energy Generation

In this Chapter, a case study is used to further illustrate the functionality of the model: The use of the electric vehicle battery to support a small-scale wind distributed generation (DG) device (wind turbine). The electric vehicle, household electrical system and wind turbine are connected to form a grid. Renewable sources of electricity tend to be intermittent generators. They do not reliably produce electricity to match demand. Wind generation produces electricity when the wind is sufficient, not necessarily when the customers demand electricity. Electricity storage would be useful in storing electricity from wind generation when demand is low so it can be used when demand is high. This case study will demonstrate use of the tool in ascertaining if electric vehicle storage is suitable for supporting a small-scale wind turbine.

This case study will demonstrate the following tool functionality:

- The capability to handle inputs from generation, in particular, variable generation in the form of a wind turbine;
- the capability to simulate vehicle usage behaviour specific to an individual; and
- the capability to control a vehicle-to-home system, taking into account the competing needs of generation and vehicle mobility.

6.1 Use Case

The use case narrative in this case study is as follows: "The customer (vehicle operator) wishes to use the battery of their electric vehicle to increase the utilisation of their wind turbine generator, while respecting their mobility requirements."

The system actors that are relevant in this case study are those outlined in Table 4.4. The electricity supplier is not an active participant. Rather, the grid is called upon to supply electricity when the wind generation or the electricity storage have failed to meet household demand. This case study will demonstrate the model operation with vehicle usage and variable generation input. Figure 6.1 shows the systems that are relevant in this case study. All of the systems have relevant inputs. The household presents a load to be met by an intermittent generator. The vehicle will be used for storage and mobility. These two functions must be balanced—there is a need for control and the results of this control on the vehicle must be output. Arguably, there is a need for generation output. The renewable generator is only an input, but the requirement for electricity from the grid that results in a failure of wind generation and storage is output from the model. Grid outputs are not highlighted in Figure 6.1 simply because these outputs refer to a different type of generation than what is the focus of the case study.

Tables 6.1 and 6.2 describe the high-level case-study in two scenarios. There are two distinct scenarios in this case study, namely, the storage of excess generation and the supply of load when there is insufficient generation. Table 6.3 describes the interactions between actors. Note that Table 6.3 describes a positive series of events. If, for example, at step three the Customer Energy Management System found that the vehicle is not available, then the process of charging from the wind turbine would be terminated.

Table 6.1: High-level description of vehicle-to-home distributed renewable excess generation scenario.

Triggering event	Primary actor	Pre condition	Post condition
Wind turbine generation is greater than the household demand	Vehicle system	Customer has electric vehicle and systems suitable for V2H, plus wind generation	Customer has successfully operated their EV in accepting excess generation from wind turbine

It follows that the key inputs are:

- Household demand;

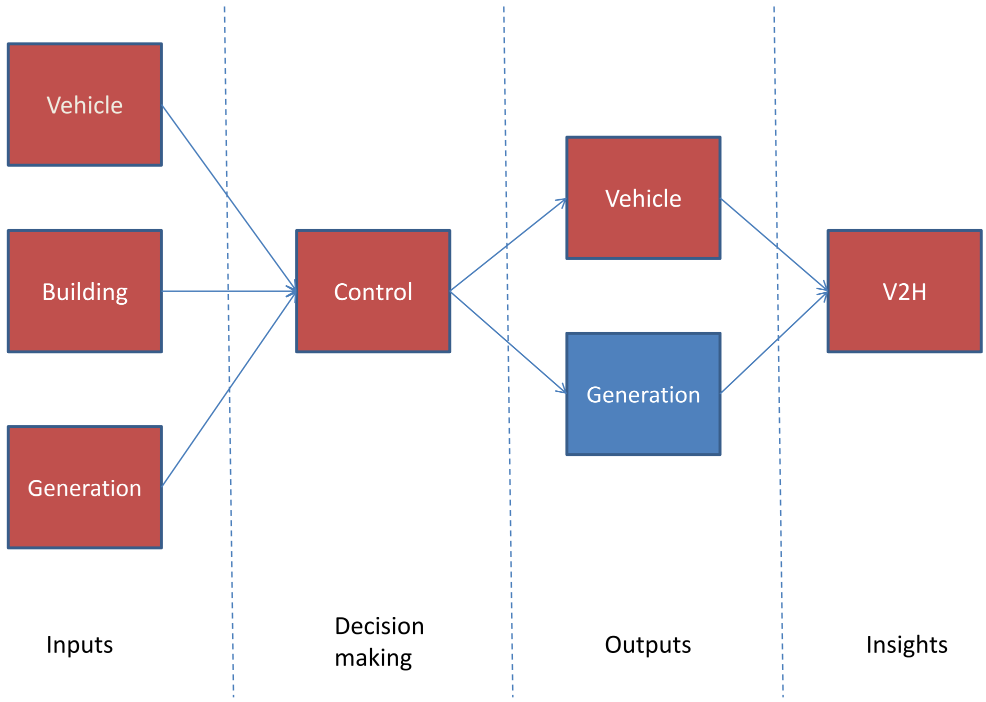

Figure 6.1: Conceptual diagram of the simulation tool; highlighted to show relevant systems in distributed generation case study.

Table 6.2: High-level description of vehicle-to-home distributed renewable storage supply scenario.

Triggering event	Primary actor	Pre condition	Post condition
Wind turbine generation is not sufficient to meet household demand	Vehicle system	Customer has electric vehicle and systems suitable for V2H	Customer has successfully operated their EV in providing power to household appliances

- generation supply;
- vehicle parameters that determine the decision to supply/not supply household load;
  - The battery state-of-charge—there must be sufficient energy to supply the load and preserve the range buffer; and
  - charging/discharging rate—to determine the change in SoC and inform on efficiency, degradation etc.;
- Vehicle parameters that determine if mobility requirements interfere with storage requirements:

Table 6.3: Step-by-step interactions between actors within a vehicle-to-home system in distributed energy generation scenario.

Step	Actor	Description of step
1	Household Energy Management System (HEMS)	Generation is in excess of household demand
2	HEMS	HEMS instructs CEMS that vehicle is required as an energy sink
2	Customer Energy Management System (CEMS)	CEMS detects if vehicle is available as an energy sink
6	Customer Energy Management System	CEMS and EV exchange information and energy storage parameters (ie. Storage capacity, state-of-charge, charging rate, discharging rate etc.)
7	Customer Energy Management System	CEMS sends control signals to EV requesting charging from distributed generator
8	EV	EV processes control messages sent from CEMS and executes them after verifying request against current vehicle parameters; ensures the SoC is sufficiently low to accept power from generation, respecting mobility requirements
9	EV	EV sends message to CEMS confirming control message and EV status
10	Household Energy Management System	There is insufficient wind power to meet household demand
11	Household Energy Management System	HEMS instructs CEMS to supply household demand from vehicle
12	Customer Energy Management System	CEMS and EV exchange information and energy storage parameters (ie. Storage capacity, state-of-charge, charging rate, discharging rate etc.)
13	Customer Energy Management System	CEMS sends control signals to EV requesting supply to household
14	EV	EV processes control messages sent from CEMS and executes them after verifying request against current vehicle parameters; ensures the SoC is sufficient to supply household demand, respecting mobility requirements
15	EV	EV sends message to CEMS confirming control message and EV status

– Vehicle availability; and

– charge required for future journeys.

The key issue follows from the narrative and is obtained by summarising the interactions between key actors: *How well does the vehicle storage improve the utilisation of the wind generation?* The measurement of this issue is not as straightforward as that in the back-up generation example. Here, a variation on turbine capacity factor* is used. The wind generator will generate a certain amount of energy over a time period. With no storage, only some of this energy will actually be used to power household appliances (since the demand for electricity may not

*Wind turbine capacity factor is the energy generated by a turbine over a time period displayed as a percentage of the nameplate generation capacity over the same period, that is, the fraction of actual energy generated and total possible energy generated.

coincide with supply). With stationary storage of infinite capacity and zero efficiency losses, all the wind energy can be used to power household appliances. Vehicle-to-home will sit somewhere between these two extremes. So, the utilisation factor will be defined as the energy used from the wind turbine (either to power appliances instantaneously or stored in the vehicle for later use) as a fraction of total energy generated by the turbine.

The utilisation factor was implemented in the tool as described in Equation 6.1.

$$UF = \frac{E_{app} + (E_{charge} \times \eta_{charge}\eta_{discharge})}{E_T} \tag{6.1}$$

where UF is the utilisation factor, E_{app} is energy from wind turbine directly to power household appliances, E_{charge} is the energy from the wind turbine stored in the vehicle battery, η_{charge} and $\eta_{discharge}$ are the charging and discharging efficiencies, respectively, and E_T is the total energy generated by the wind turbine over the time period.

There are some issues with this measure of the effectiveness of V2H in supporting the turbine. In certain circumstances, energy from the wind turbine could be stored in the vehicle battery but not used for any useful purpose. For example, if an amount of energy is transferred to the vehicle in the morning then the vehicle is disconnected from the household and not used for mobility the energy from the wind turbine has served no useful purpose. However, this situation cannot continue for extended periods. Eventually, the battery SoC will reach its maximum and no more wind energy can be stored. The example outlined is also unrealistic, it proposes that the vehicle owner is hoarding wind energy of no purpose—no driving use and not support of renewables—this seems unlikely. A converse situation can be envisaged, this measure of utilisation ignores occasions when the household is powered from the vehicle using energy not from the wind turbine. Again, this situation is unsustainable since the energy stored in the battery must come from somewhere. Since vehicle charging away from the household is not considered here, this is a closed system, and the proposed definition of utilisation factor is appropriate. If a second wind turbine is introduced, at the workplace for example, then a new definition of utilisation factor may be required.

6.2 Generation Input

The model requires an input of power generated versus time. In the case of wind generation the supply profile is dependant on the wind speed[†]. The model simulates a small-scale wind turbine using a look-up table. Wind speed incident on the turbine is input and is converted to power output. The wind turbine will not provide power below a minimum windspeed or above a maximum windspeed. Figure 6.2 shows the values of the look up table for converting wind speed to power output. The look-up table is based on a commercially available 2.4 kW wind turbine.

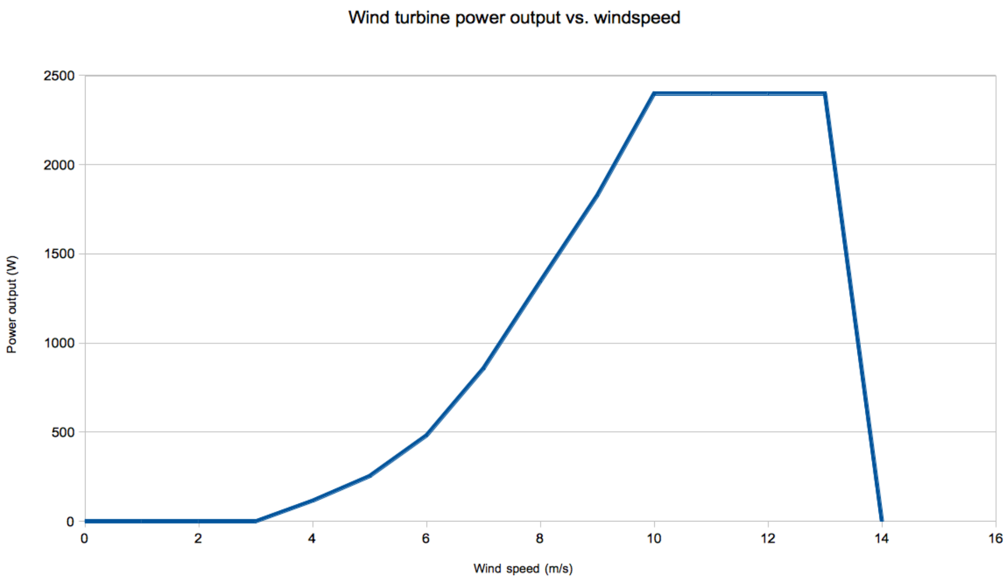

Figure 6.2: DG case study; Graph of look up table for wind turbine; power output vs. wind speed.

Figure 6.3 shows the implementation of the lookup table in the Simulink model.

Similar to household demand data, it is difficult to obtain wind speed data with a time interval less than thirty minutes. The Royal Netherlands Meteorological Institute (KNMI) collects and publishes daily wind speed data recorded at several Dutch wind turbine sites. Figure 6.4 shows the power output from the wind turbine using KNMI data from its Valkenburg site; the household demand that will be assumed is also shown. The fact that the wind speed data is from The Netherlands and the household data is from the UK is not important. The aim of this case study

[†]It is also dependent on the quality of the wind incident on the turbine; turbines requiring laminar flow; for a discussion of the use of wind speed data to estimate power output, see Sinden [44].

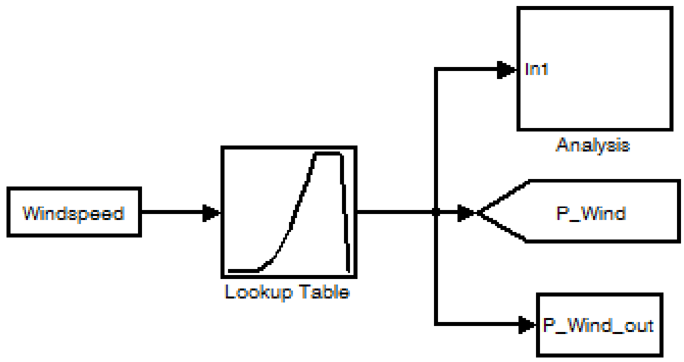

Figure 6.3: Simulink model to simulate the power generated from the wind turbine.

is to demonstrate the functionality of the model. To this end, all that is required is a profile for an intermittent power supply. Actual wind speed data is used here to ensure the experiment is at least realistic in its assumptions.

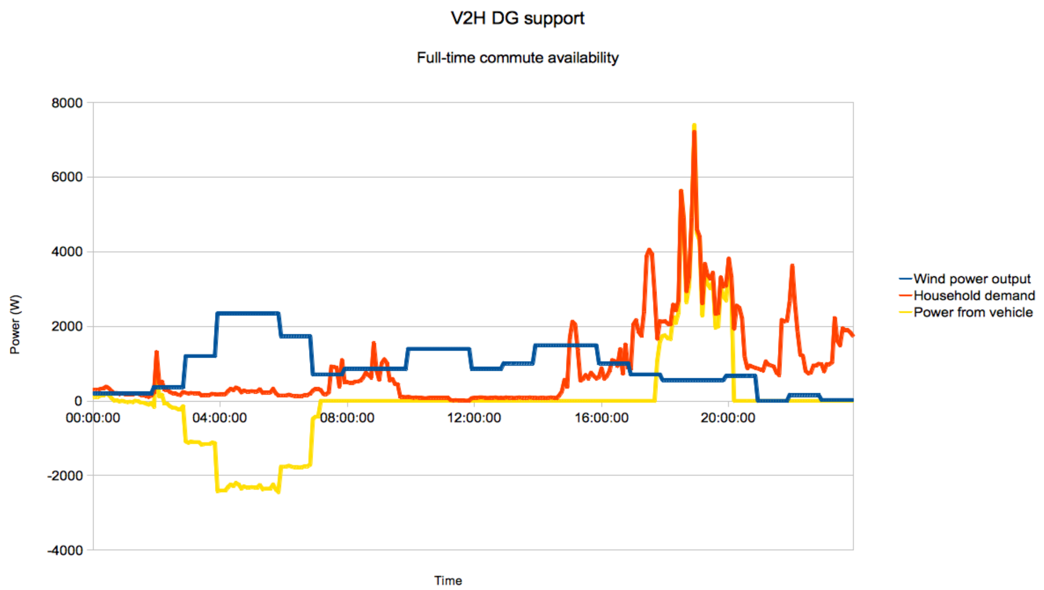

Figure 6.4: DG case study; full-time commute availability; generation, demand and vehicle storage use.

The datasets for wind power output and household demand, while both recorded from midnight to midnight, are for different days. There are several reasons for choosing to superimpose these data. The wind turbine never supplies sufficient power to meet the peak household demand. Also that the peak generation does not match with peak demand. Peak demand for the household on this day occurs in the evening—when the UKs aggregate peak demand occurs. One challenge for

V2H is that the vehicle is expected to provide power in the evening peak time, after a commuting journey has occurred (and the battery is depleted). The data superposition in Figure 6.4 could be used to test V2H in this scenario.

6.3 Model Setup

Table 6.4 contains the basic parameters used in the first experiment.

Table 6.4: Vehicle Parameters for First Experiment.

Parameter	Value
Battery Capacity	24 kWh
Initial SoC	50%
Range Buffer	15 miles
Charging Efficiency	90%
Discharge Efficiency	90%
Driving Distance	44 miles

The parameters are the same as those used in the first experiment of the back-up generation case study, apart from the initial SoC. A distributed generation case study requires power flow into and out of the storage device. This makes the issue of initial SoC and capacity more interesting; a fully charged battery cannot accept charge from a generator, and an empty battery cannot supply a load. Since the battery is required to do both these things during its operation the initial SoC may have a bearing on vehicle-to-home operations. For example, an initial SoC of 100% is preferable for serving vehicle mobility needs, but if there is an excess of wind generation then the vehicle cannot act as a sink. Sensitivity to initial SoC as an input parameter will be explored in Section 6.5.

It was assumed that charging only took place at home. If charging at work (or elsewhere) is an option, then this simply increases the battery energy available for vehicle-to-home—sensitivity to this variable can be tested by varying, for example, the total battery capacity, journey distance or range buffer.

A journey distance of 22 miles per trip accounts for 90% of UK journeys [6], so is a reasonable assumption. Again, sensitivity to battery energy availability can be tested in experiments. Using Nissan Leaf driving efficiency assumptions, a 22 mile journey requires 4.8 kWh.

6.4 Vehicle Use

The first experiment in this case study will explore varying vehicle availability. Three different vehicle availability time series were used.

1. A full-time workers commute;
2. a part-time workers commute; and
3. a school run.

Table 6.5 summarises the departure and arrival times (from and to the household) for the three vehicle availability profiles used.

Table 6.5: Three vehicle availability profiles for the first experiment.

	Depart	Arrive	Depart	Arrive
Full-time commute	7:10	17:45	-	-
Part-time commute	7:50	12:30	-	-
School run	8:00	9:00	15:00	16:00

While the vehicle is away it is assumed that it will complete two journeys, so the total distance travelled is 44 miles—9.6 kWh. That is, apart from the school run where it is assumed that four trips are completed, with a total of 44 miles (11 miles per trip), so in each journey period 4.8 kWh is required. As outlined in Section 4.5.1, driving energy use is simulated in the model as a constant power draw while the vehicle is away from the household. The constant power draws that simulate the driving in this experiment are summarised in Table 6.6.

Table 6.6: Simulated power draw for driving use in first experiment.

	Power (W)
Full-time commute	900
Part-time commute	2,021
School run	2,215

Vehicle availability raises a legitimate concern with the datasets used in this case study: The vehicle use assumptions do not match the household data. Household energy use is related to occupancy of the household (many appliances are not used if the occupant is not present.) The low energy household would not be a sensible choice to use in this case study since it only has one occupant. When the occupant is driving, the household energy use should be lower—there is room for discrepancies. Choosing the high demand household, with its six residents, at least gives leeway to the assumption that one of the occupants is driving while energy is being used as presented in the household demand profile.

In this first experiment, additional requirement for vehicle charging was ignored to simplify the inputs. The Charging Time input was overridden so the vehicle does not interrupt vehicle-to-home operation to charge. Figure 6.4 shows the wind generation and household demand versus time, along with a tool output showing power to and from the vehicle storage. Between 3:00 and 7:00 the wind generation exceeded the household demand. The excess generation was therefore stored in the vehicle battery (shown on Figure 6.4 as negative power from the vehicle). From 7:10 to 17:45, the vehicle was away from the household, it therefore cannot provide storage. No power flowed between the wind turbine and vehicle or the vehicle and household during this period. At several times during this period the household demand exceeded the generation of the wind turbine. This unserved load must be met by other means, the model outputs this unmet power versus time as "from the grid", assuming that a connection to the national grid will serve load if required. Also while the vehicle is unavailable, the turbine generates electricity excess to requirements that cannot be stored for later use. Again, the model records this power as "to the grid" assuming the grid can act as a sink to distributed generation if required.

When the vehicle becomes available for vehicle-to-home again, the household demand was in excess of the wind generation and the storage energy of the battery was used to power the household. The vehicle was used to support much of the evening peak until the battery SoC fell to the 3kWh minimum at 19:50 and vehicle-to-home ceases. The forced stopping of vehicle-to-home to preserve the range buffer was unfortunate, since storage was still required to provide power to the household. The battery SoC variation over the day is shown in Figure 6.5. Note the falling SoC when the vehicle is away from the household. This constant power draw simulates the commute; it is a constant power draw of 900W.

The utilisation factor for the full-time commute availability is presented in Table 6.7; the individual elements of Equation 6.1 are presented for reference.

The model was run with the same parameters as with the full-time commute but with different vehicle availability profiles. Figure 6.6 shows the power flow to and from the vehicle over the day and the battery SoC variation for the part-time commute vehicle availability. With part-time commute availability, the vehicle is

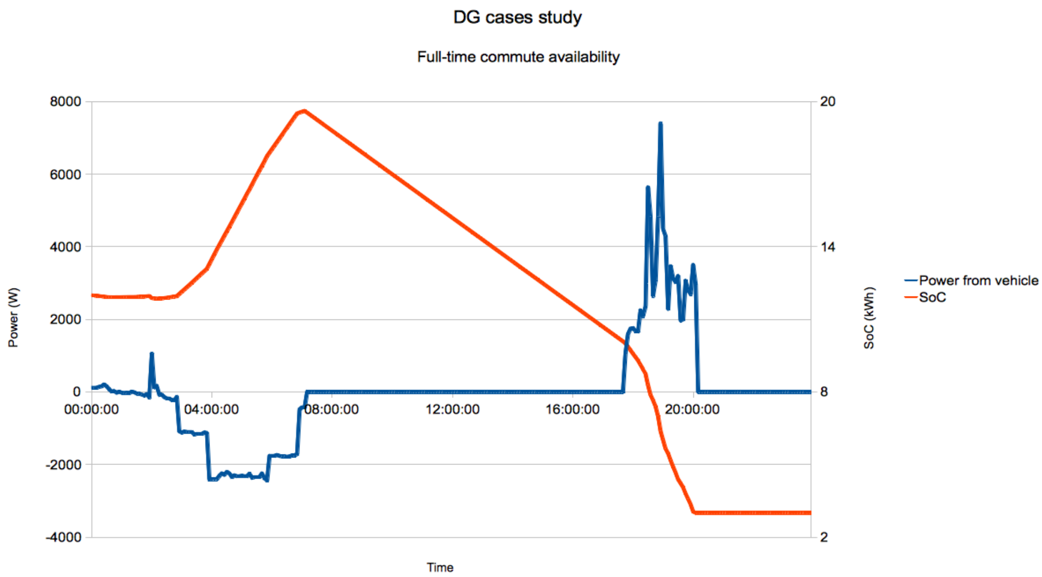

Figure 6.5: DG case study; full-time commute; battery SoC variation and vehicle storage use.

Table 6.7: DG case study; full-time commute; utilisation factor.

Output	Value
Utilisation Factor	64%
E_{app}	7.9 kWh
$E_{charge}\eta_{charge}\eta_{discharge}$	6.3 kWh
E_T	22.1 kWh

available to provide V2H services more of the time. The vehicle is available to draw excess power generation more of the time and is available to supply the household demand more of the time. This is reflected in the utilisation factor and energy stored in the vehicle presented in Table 6.8 which are an improvement on those in Table 6.7.

Table 6.8: DG case study; part-time commute; utilisation factor.

Output	Value
Utilisation Factor	78%
E_{app}	7.9 kWh
$E_{charge}\eta_{charge}\eta_{discharge}$	9.5 kWh
E_T	22.1 kWh

Figure 6.7 shows the power flow to and from the vehicle and the battery SoC over the time period for the school run availability profile. The vehicle is available for more of the time period than in either commute availability profiles. Again, more excess generation is transferred to the vehicle and the vehicle provides power to the household until the end of the time period—the vehicle SoC never reaches its

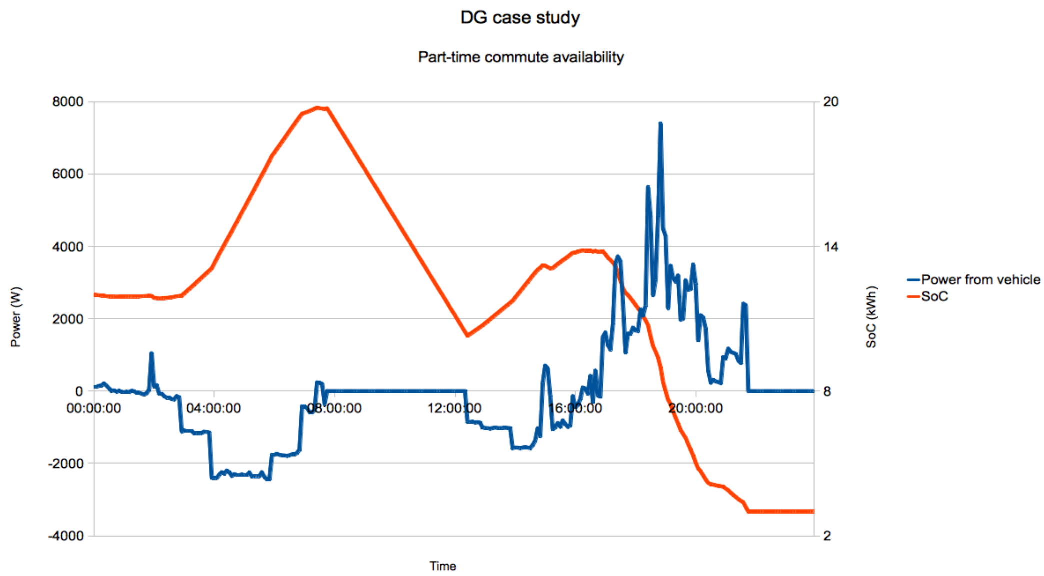

Figure 6.6: DG case study; part-time commute; battery SoC variation and vehicle storage use.

minimum as in the commuting examples. The utilisation factor is shown in Table 6.9.

Note that, at 14:45 the battery SoC reaches its maximum capacity and can charge no further even though the wind turbine is still generating excess power. This situation arises from the combination of excess generation from the wind turbine for much of the earlier part of the day and limited use of the vehicle for driving. It seems sensible in this case to reduce the initial SoC to lower than 50%. The SoC at 23:55 was 7.5 kWh; an initial SoC of 10 kWh would accommodate the peak at 14:45 and the SoC would always remain above the 3kWh minimum.

However, note that the final SoC for one time period is the initial SoC for another. Over the day presented in this case study, the final SoC was lower than the initial SoC—this is not sustainable[‡] operation. To ensure the operation is sustainable, the energy from the battery must be replaced; if not from the wind turbine then by other means. Charging time is required and its effect on V2H operation explored.

Table 6.9: DG case study; school run availability profile; utilisation factor.

Output	Value
Utilisation Factor	90%
E_{app}	7.9 kWh
$E_{charge}\eta_{charge}\eta_{discharge}$	11.9 kWh
E_T	22.1 kWh

[‡]In the sense that it cannot be sustained over repeated periods of time. Not in the sense of environmental sustainability.

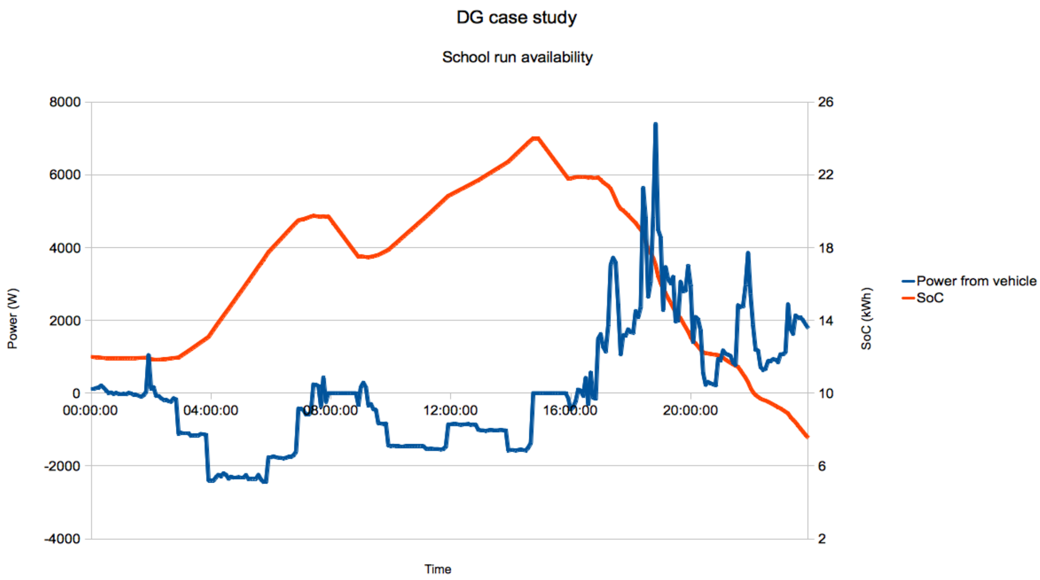

Figure 6.7: DG case study; school run; battery SoC variation and vehicle storage use.

This experiment confirmed an intuitive result: That if the vehicle is available more longer periods of time then it is more useful for vehicle-to-home services. Using the tool allowed this qualitative statement to be quantified for certain time series data. The tool is flexible such that any time series data for a household, generator and vehicle can be input and used to analyse vehicle-to-home operation in that situation.

6.5 Charging Time

In the second experiment of this case study, charging time is introduced to the system. Sufficient charge must be input to the vehicle battery to ensure it can meet its mobility needs. The operation of the vehicle must also be sustainable over multiple time periods. There will likely be variation in the operation of each of the V2H systems from day-to-day, so, a slight difference in initial and final SoC over one time period may be balanced out in the next. But consistently draining the battery over a time period is not sustainable and, at some point, the battery must be charged.

The model was run with the same parameters as the previous full-time commute case study except that time was set aside for charging the vehicle. The vehicle was charged to replace the 9.6 kWh required for the journey. Including charging efficiency losses this equates to 3.56 hours of charging with a 3kW power source[§]. Two charging times were tested, both overnight:

1. Early morning: 00:00 to 03:35; and

2. late evening: 20:20 to 00:00.

Figure 6.8 shows the battery SoC and the power to and from the vehicle battery for the early morning charging time. The SoC climbed as charging occurred up until 03:35; the SoC continued to rise as excess power was available from the wind turbine. The morning charge prevented vehicle-to-home taking place but ensured that the battery SoC was high before the vehicle was used for driving. However, the maximum SoC was reached at 4:40 when excess power was available from the wind turbine. Note that, even though the energy used in driving is replaced during charging time, the V2H operation over this period was not sustainable—the final SoC was lower than the initial SoC. The excess wind turbine generation that could have been stored in the vehicle had the charging not taken place early in the day, would have helped make V2H operation sustainable over the time period.

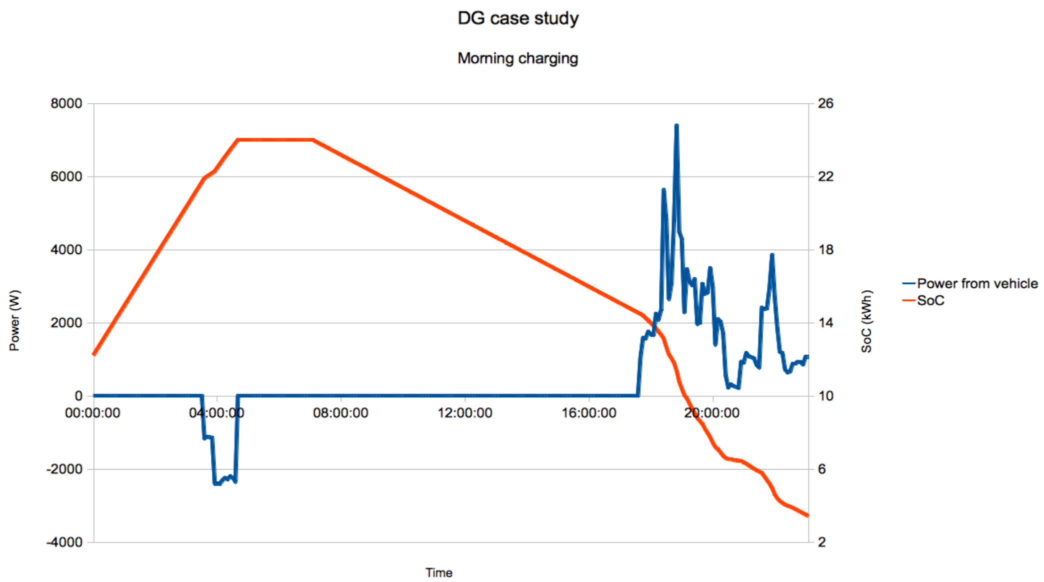

Figure 6.8: DG case study; morning charging time; battery SoC variation and vehicle storage use.

A utilisation factor of 43% results from $E_{charge}\eta_{charge}\eta_{discharge}$ of 1.7 kWh.

[§]3kW is a fair assumed charging rate since it can be achieved with any UK single-phase household supply.

Figure 6.9 shows the battery SoC and power to and from the vehicle for the evening charging time. The vehicle charging can be seen as the rise in battery SoC from 20:20 to midnight. Delaying the vehicle charging to the late evening has great effect on the operation of vehicle-to-home over the time period. The excess wind generation between approximately 04:00 and the departure time was stored in the vehicle battery and then used for driving. Much of the evening household demand peak was served by the vehicle. The late evening charging time does clash with some household energy demand, but the lack of excess wind generation meant no storage was required during the charging time. The utilisation factor for evening charging was 64%, given $E_{charge}\eta_{charge}\eta_{discharge}$ of 6.3 kWh. The evening charging time regime was also sustainable, with the initial and final battery SoC being approximately equal.

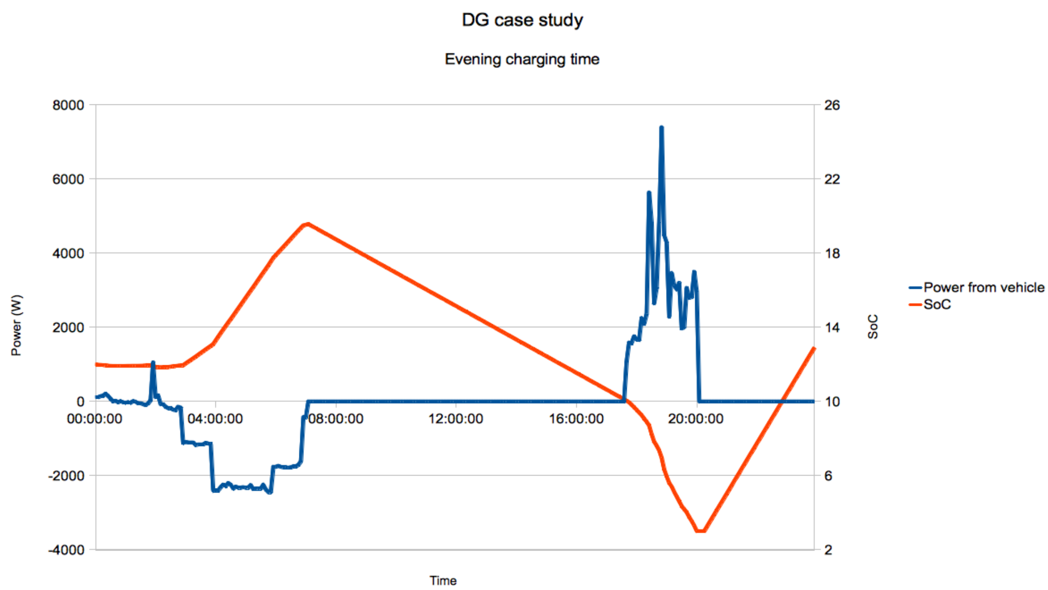

Figure 6.9: DG case study; evening charging time; battery SoC variation and vehicle storage use.

The timing of charge is relevant to the operation of vehicle-to-home. Ideally, the vehicle battery SoC will always be sufficiently low to accept excess power from the wind turbine; but always sufficiently high to supply the household if necessary and meet mobility needs. The experiment of this Section—varying the time of day of charging—has shown that it is not only the amount of energy that is input to the vehicle that is important, but when the charging takes place. With the household demand, vehicle usage and wind generation profiles used in the experiment of this

Section, evening charging was superior (from a V2H perspective) to morning charging. However, with different profiles, a different charging time may be appropriate.

With the simulation tool and the time to complete experiments, the optimal charging time for a given set of variables can be determined. In a real vehicle-to-home system the profiles for vehicle usage, household demand and generation from wind are unknowns. The setting of system parameters to control the vehicle-to-home system must involve some element of estimation.

6.6 Range Buffer

The final experiment in this case study was used to explore the range buffer parameter and its effect on V2H operations. Three different range buffer values were used. Expressed in kWh of battery energy as 0 kWh, 10 kWh and 20 kWh. Or expressed in miles as (approximately) 0 miles, 46 miles and 92 miles. The larger range buffer value is unrealistic[¶] and was chosen only to demonstrate the capability of the model and to explore sensitivity to the range buffer parameter.

For this experiment, the same parameters were used as in the evening charging experiment. That is, full-time commute availability, high household electricity demand and vehicle parameters as in Table 6.4. Figure 6.10 shows the battery SoC variation and the power to and from the vehicle for all three range buffer values.

Figure 6.10 shows similarity between the three different range buffer values; this similarity is informative. In the model runs with 0 kWh and 10 kWh range buffer values the initial SoC was higher than the minimum SoC; with a 20 kWh minimum SoC the initial SoC was lower than the initial SoC. However, the wind generation and household demand profiles over the time period call for the vehicle battery to store energy between approximately 04:00 and 7:10 so V2H was allowed in all three cases. This fact is reflected in the near identical SoC variation and power to the vehicle from 0:00 until the vehicle returned from its commute. Note that there was power flow from the vehicle to support household demand from 0:00 to 0:40 in the 0 and 10 kWh runs, but no power flow from the vehicle at this time in the 20kWh run, precisely because the initial SoC was lower than the 20 kWh range buffer.

[¶]A range buffer of 92 miles in a vehicle with a 110 mile range amounts to a refusal to participate in V2H. This is a valid position for a consumer to take, but if this position is taken the vehicle is no longer of interest from a V2H perspective.

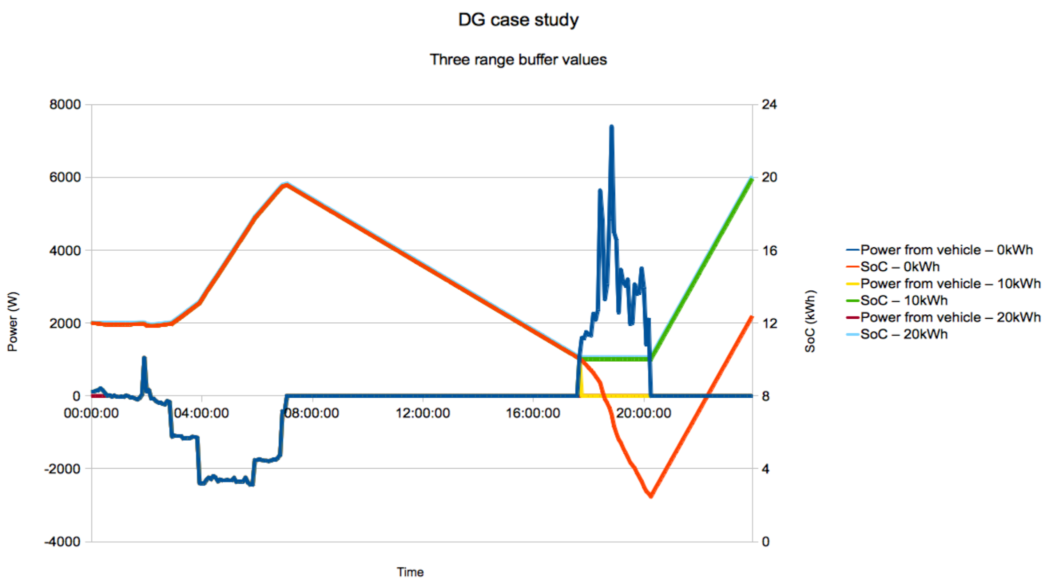

Figure 6.10: DG case study; three range buffer values.

At 17:45 the operation in the three cases diverge. In the 0 kWh range buffer example the model judges that there is sufficient battery SoC to supply the evening household peak. The vehicle supplied the household and the battery SoC fell to 2.5 kWh before vehicle charging commenced. In the 10 kWh case the SoC was 10.1 kWh on returning from the commute, so the vehicle supplied household power demand for less than 5 minutes before the battery SoC fell to the range buffer and V2H operation ceased. The battery SoC remained at 10 kWh until charging time commenced. In the 20 kWh range buffer example the battery SoC was 10.12 kWh on returning from the commute. Since this was below the 20 kWh range buffer the vehicle was not used for vehicle-to-home and the SoC remained at 10.12 kWh until charging time commenced.

The utilisation factor for all three range buffer values was 64%. This is because the amount of energy transferred to the vehicle from the wind turbine in all three cases was equal. The transfer of wind energy to the vehicle happened early in the day, and even though the range buffer was already violated in one case there was sufficient capacity to accept energy from the wind turbine in all cases (from 04:00 till 07:10). The weakness of using utilisation factor as a measure of success was discussed at the beginning of this Chapter. One could argue that the energy stored in the 20 kWh and 10 kWh examples may be used at a later time. However, there is a difference in the operation of the 0 kWh range buffer and 10 and 20 kWh range buffer examples and this should be explored.

When the vehicle does not provide V2H service and the wind turbine is not generating sufficient energy the household energy must be supplied from an external source. Figure 6.11 shows the power to and from "the grid" for all three range buffer values.

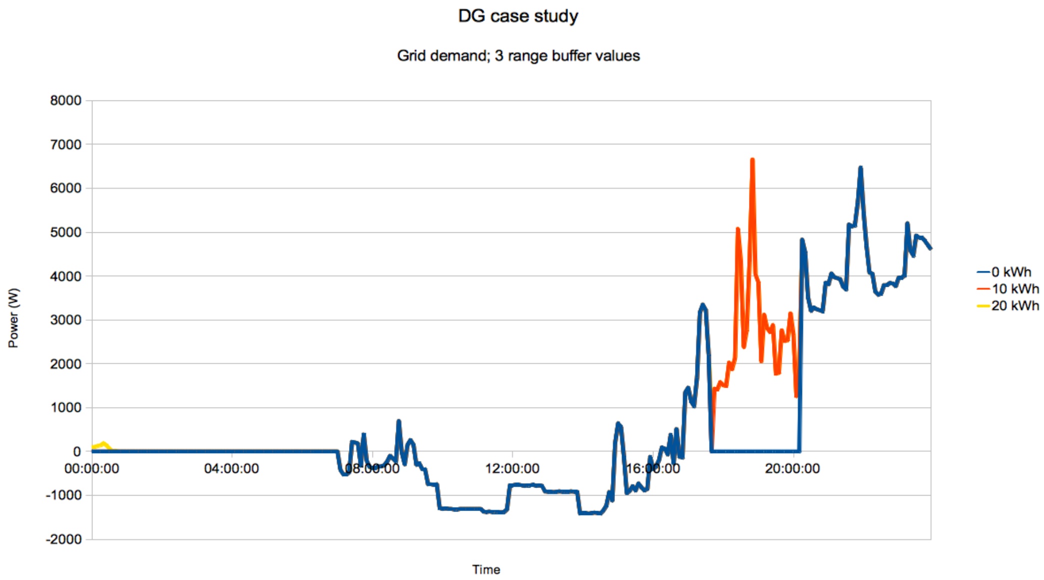

Figure 6.11: DG case study; three range buffer values; grid demand.

The grid supplied the household from 0:00 to 0:40 in the 20 kWh case, as already discussed. In all three range buffer examples the grid supplied the household, but also accepted excess wind generation, while the vehicle was away from the household. However, the most obvious difference between the three range buffer values was between 17:45 and 20:10: In the 0 kWh range buffer example the vehicle supplied the household demand at this time; in the 10 and 20 kWh range buffer examples the demand at this time was supplied from the grid.

Note that, in all three range buffer cases the grid was relied upon to supply the vehicle charging and the household demand in the late evening. Considering the implications on the wider electric grid outside the remit of this distributed generation case study. However, this range buffer experiment serves to highlight the fact that, even with vehicle-to-home operation, an external energy source[‖] may be required. Further, that the parameters of vehicle-to-home operation will have an impact on

[‖]Or extra energy storage. The use of stationary storage in conjunction with vehicle-to-home could be explored. In the range buffer experiment, a smaller stationary storage unit would be required with the 0kWh range buffer, since it would be called upon to supply less household demand.

how this external source operates.

Note that, even considering the wider grid implications, the 10 kWh and 20 kWh range buffer values gave almost identical results. This shows that, in certain operational conditions, setting an apparently much lower range buffer will have limited impact on the operation of the vehicle-to-home system.

There is an argument that energy storage is not required for a small-scale generator such as the one studied here. The electricity grid has limited renewable energy generators at present. Any energy generation from renewable generation is simply an input to the grid, essentially as a base load. Any mismatch of supply and demand is managed by varying power station output of catered for by gas turbine generation. In Germany, the percentage of wind generation recently passed 9% of the total grid mix, apparently without any intermittency issues [45].

However, wind is an intermittent energy source. Wind generation could not be relied upon as 100% of the grid mix and storage could be used to match intermittent supply with intermittent demand [46]. Further, adding small scale generation to the electricity grid is not without challenges. An increase in distributed generation presents issues with grid fault current management [47].

7

Further Work

This Report has outlined a different approach to the analysis of vehicle-to-home. This different approach to analysis is necessary for understanding vehicle-to-home as a nascent technology. The strengths of the approach arise from its addressing this necessity—the vehicle-to-home tool presented enables the individual consumer to be the focus of the analysis; also, the tool is sufficiently flexible to study different application of V2H.

7.1 Validation

Some validation work was completed while the Simulink model was in development. Each of the subsystems was tested with simplified inputs. For example, the battery storage simulation was tested with a constant power input over a given time period. The results from the model were then compared with manual calculations. Similar validation was completed using simple inputs for each subsystem involved.

However, further validation activity would add rigour to the simulation tool results. The first step in validation would be to build a similar vehicle-to-home system in third party energy system software (for example, Plexos by Energy Exemplar). The results of the two models could then be compared.

The next step in validation would be the use of laboratory hardware (a real battery) operating to simulate vehicle-to-home operating conditions. This would give insight into the operation of a battery in near real vehicle-to-home operation.

Ultimately the results of the simulation tool should be compared with a real vehicle-to-home system. The use of an actual electric vehicle as an energy storage device in a vehicle-to-home application would give real insight into how user behaviour varies. The actual use of the vehicle-to-home system would provide realistic inputs for the simulation tool; results from the tool could be compared to the real life results.

The development of this tool is the first stage in a learning process. The work carried out here suggests vehicle-to-home is feasible in certain situations. The validation work would be a continuous improvement process. As more realistic systems are developed and included, the model can be updated to improve its fidelity.

7.2 Tool Developments

Confining the scope of study to an individual vehicle and household makes it difficult to establish the impact of the vehicle-to-home system on the wider electricity network. The UK Ancillary Services market provides an illustrative example. An electric vehicle could in principle offer Firm Frequency Response (FFR) services; the vehicle can act as a sink or a source to help raise or lower grid frequency as required. However, the impact an individual vehicle can have on the grid is negligible. In the UK, National Grid require an FFR service provider to provide a minimum of 10MW power to or from the grid. Given that an electric vehicle, via its charging point, will provide or draw tens of kW electrical power, a single vehicle is a negligible actor in the market.

Regulatory requirements can be changed, but it is necessary to know how many vehicles must be aggregated to have an impact in a market like the ancillary services market. Modelling such impact becomes difficult since the introduction of vehicle-to-grid to an existing market will alter its economics. The values that determine the economics of the current market cannot be used to determine the economics of the new and different market.

Eventually, the number of electric vehicles in the car parc will be large enough that analysis using averages will be valid. There will be a crossover point where the approach described here will be unnecessary and the simpler, averaged models can be applied. Expanding this tool to multiple vehicles will allow this crossover point to be established. Expanding the tool to multiple vehicles will also allow other configurations of vehicle-to-grid to be explored. Of particular interest would be the use of several electric vehicles in a single street to provide energy storage to several households in that street.

The physical model implemented here can be improved. In particular, better battery characterisation would improve the tool. As noted, battery lifetime is a significant issue in the feasibility of vehicle-to-home. The tool provides outputs that could be used to determine battery degradation, given an appropriate model. But it would be useful to have this characterisation built into the tool.

In this report, the use of the tool was largely to demonstrate its capabilities. To complete a thorough analysis of vehicle-to-home using the tool would require detailed datasets of vehicle usage, household energy demand and generation requirements is needed.

It would be interesting to explore consumer attitudes to the input parameters. For example, it would be useful to understand what range buffer consumers would require if they participated in a vehicle-to-home or vehicle-to-grid system. It would be difficult to establish an accurate figure, since most people have no experience with electric vehicles, and no experience of vehicle-to-home. Range anxiety is a problem associated with electric vehicles, and while the range buffer should alleviate range anxiety concerns with vehicle-to-home, the issue should be explored with consumers.

The tool could also be used to explore vehicle-to-grid business models. In particular, to determine if the proposed business models require vehicle-to-grid operation that is compatible with consumers lifestyles. The tool could be used to determine the potential for vehicle-to-home for a given consumer, and thus be used to establish value propositions.

Finally, to ensure the model is used, it should be user friendly. The development of a graphical user interface would help in this regard.

8

Conclusion

An introduction to the vehicle-to-grid concept was presented. A review of the relevant literature was presented via the identification of barriers to V2G implementation.

This review highlighted gaps in the understanding of vehicle-to-grid. Notably:

- Existing models do not allow a time-series analysis of the use of vehicle storage for vehicle-to-grid and therefore do not capture variation due to people's behaviour. Existing models are only capable of using average data as inputs and so are only valid for assessing the feasibility of vehicle-to-grid when many vehicles are available for use as storage; existing models cannot be used to assess the feasibility of vehicle-to-home on an individual case by case basis.
- Existing models are only suitable for analysing the feasibility of vehicle-to-grid in applications where vehicle storage is aggregated. Since distributed storage, embedded at the electricity distribution grid level, will be of more value than bulk storage, this limitation of existing models should be remedied.

An analysis of the maturity of the technology using the Technology Readiness Levels framework highlighted that the field of vehicle-to-grid research has progressed too quickly to the technology demonstration phase. Further research into the feasibility of vehicle-to-home was required.

Since existing models of vehicle-to-grid operation are not suitable for addressing the highlighted gaps, a new approach to the modelling of vehicle-to-home systems was required. The following research objectives were stated:

- Develop an approach to modelling vehicle-to-home that enables a sensitivity analysis of user determined inputs and their granularity;

- Demonstrate that this approach can be used to study distributed storage applications that could not be studied with previous approaches;
- Demonstrate this approach in a vehicle-to-home system such that it provides outputs not possible with previous approaches; and
- Describe the differences, or lack thereof, of this and previous approaches.

A simulation tool was developed consisting of two parts: the application of the use case methodology to determine the system actors and their actions; and the use of a model—based in Matlab Simulink—to simulate the vehicle-to-home system. Used together, the two aspects of the tool ensure the vehicle-to-home system is simulated with a user behaviour focus and with better granularity than in models presented in the literature.

The use of the tool was demonstrated in two case studies: the use of an electric vehicle as a back-up supply for the household should the grid power supply fail and the use of an electric vehicle to store energy from a small wind turbine and use this energy to supply the household.

The backup supply case study demonstrated the capability of the simulation tool to:

- Handle granular household electricity demand data; and
- simulate some aspects of an electric vehicle used for storage.

Sensitivity to the following input parameters was explored: household electricity demand, battery capacity and charging/discharging efficiency.

As can be expected, the back-up electricity supply from the vehicle lasted longer when household electricity demand was lower. Even in the highest demand case, the vehicle supply still lasted 22 hours. The longevity of back-up supply increased approximately linearly with battery capacity. Higher discharge efficiencies resulted in longer back-up supply, the effect of efficiency on longevity of supply was significant.

The distributed renewable energy generation case study demonstrated the capability of the simulation tool to:

- Handle inputs from variable distributed generation in the form of a wind turbine;

- simulate vehicle usage behaviour specific to an individual; and
- control a vehicle-to-home system, taking into account the competing needs of generation and vehicle mobility.

Sensitivity to the following input parameters was explored: vehicle use for driving, timing of vehicle charging and range buffer. The success of the vehicle in providing storage for the wind turbine was measured by a utilisation factor. Utilisation factor was defined as the useful energy from the turbine as a fraction of the total energy generated by the turbine.

Higher utilisation factors were realised when the vehicle was available for vehicle-to-home more of the time (when the vehicle was used less for driving). Utilisation factor ranged from 64% when the vehicle is used for a full-time commute driving pattern to 90% when the vehicle is used for a school run driving pattern. Even in the full-time commute case, excess wind generation was stored at certain times thus improving the utilisation of the wind turbine.

The study of various driving patterns highlighted the need to have dedicated charging time to replace battery energy used for driving and ensure vehicles usage is sustainable. A late evening charging time slot and an early morning charging time slot were tested with the tool. The timing of charging had a great effect on the utilisation factor, with the morning charge resulting in a utilisation factor of 43% and the evening charge resulting in a utilisation factor of 64%. The different utilisation factors resulted largely from the timing of wind generation and the battery state of charge; by charging in the morning the vehicle battery was full when wind generation was available.

Three different range buffers were input to the tool. Surprisingly, there was little difference when a 10kWh range buffer was imposed versus a 20kWh range buffer. Again, this result highlighted the importance of timing of usage of the vehicle, household usage of electricity and the timing of generation from a variable source.

The case studies demonstrated that the simulation tool can produce quantified results for various time series data inputs in novel distributed storage applications. This was not possible with existing models of vehicle-to-grid operation, which were not suitable for analysis with time-series data. Time-series data allow for variability resulting from user behaviour and from variable generation sources to be explored. The case studies demonstrated that this variability must be considered and has a significant impact on the operation of the vehicle-to-home system.

The simulation tool developed herein has given insights that could not be gained using existing models of vehicle to grid. The development of the simulation tool therefore represents a novel and innovative addition to the field of vehicle-to-home research.

Both case studies demonstrated that, given the correct conditions—notably cooperation of the vehicle user—vehicle-to-home can operate successfully in storage applications. It is the view of the author that vehicle-to-home is a viable concept in certain applications. Distributed storage applications could form a significant value stream for electric vehicles operating vehicle-to-home. Electricity distribution grid applications are particularly promising and should be explored before bulk vehicle-to-grid applications are considered. An electric vehicle acting as an energy storage system could be used to defer the upgrade of distribution grid assets. This application should be explored in more detail, but the distributed generation case study has shown that V2H could aid the placement of small-scale storage on a distribution grid, reducing peaks and therefore potantially deferring upgrade requirements.

However, significant issues remain. The work herein has shown that variability of vehicle usage and electricity usage, combined with a variable generation output strongly determines the operation of a vehicle-to-home system. Intelligent forecasting of these variables would likely be required—this would of course add cost and complexity to the system. Ownership issues, particularly of the vehicle battery, also remain. Significant work is required to ensure that the battery owner enjoys the benefits of vehicle-to-home, and that the owner does not damage their battery while only passing on benefits to, for example, the grid operator.

References

[1] I. Beausoleil-Morrison et al. An experimental and simulation based investigation of the performance of small scale fuel cell and combustion based cogeneration devices serving residential buildings. *Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme*, 2008.

[2] S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. M. Miller. Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. *Intergovernmental Panel on Climate Change*, 2007.

[3] The Committee on Climate Change. The fourth carbon budget: reducing emissions through the 2020s. 2010.

[4] R. L. Hirsch, R. H. Bezdek, and R. M. Wendling. Peaking of world oil production: Impacts, mitigation and risk management. *DOE NETL*, 2005.

[5] The UK low carbon transition plan. *Department of Energy & Climate Change*, 2009.

[6] Low carbon transport: a greener future. *Department for Transport*, 2009.

[7] Regulation (EC) no. 443/2009 of the European parliament and of the council. *Official Journal of the European Union*, 2009.

[8] New car CO_2 report 2009. *Society of Motor Manufacturers and Traders*, 2009.

[9] R. Webster. Can the electricity distribution network cope with an influx of electric vehicles? *Journal of Power Sources*, 80:217–225, 1999.

[10] Investigation into the scope for the transport sector to switch to electric vehicles and plug-in hybrid vehicles. *Department for Business, Enterprise and Regulatory Reform and Department for Transport*, 2008.

[11] M. Kinter-Meyer, K. Schneider, and R. Pratt. Impact assessment of plug-in hybrid vehicles on electric utilities and regional US power grids. Part 1: technical analysis. *Pacific Northwest National Laboratory*, 2007.

[12] K. Bullis. Smarter chargers for electric vehicles. *Technology Review*, March, 2010.

[13] J. Gartner. Distribution side: grid needs to plan for plug-in vehicles. *SmartGridNews.com*, accessed August 2013. http://www.smartgridnews.com/artman/publish.

[14] L. Schewel, M. Brylawski, A. B. Lovins, C. Burns, K. Chan-Lizardo, B. Cohen, A. Demaria, M. Gately, L. Hansen, N. Harvey, S. Johns, C. Low, J. Ponce, C. Riley, M. Simpson, K. Wang, L. Wells, and J. Wilson. Smart Garage charette report. *Rocky Mountain Institute*, 2008.

[15] W. Kempton and S. Letendre. Electric vehicles as a new power source for electric utilities. *Transportation Research Part D*, 2D, 1997.

[16] W. Kempton and J. Tomić. Vehicle-to-grid power fundamentals: calculating capacity and net revenue. *Journal of Power Sources*, 144(1):268–279, 2005.

[17] W. Kempton and J. Tomić. Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. *Journal of Power Sources*, 144(1):280–294, 2005.

[18] B. K. Sovacool and R. F. Hirsch. Beyond batteries: an examination of the benefits and barriers to plug-in hybrid vehicles (PHEVs) and a vehicle-to-grid (V2G) transition. *Energy Policy*, 37:1095–1103, 2009.

[19] J. Tomić and W. Kempton. Using fleets of electric-drive vehicles for grid support. *Journal of Power Sources*, 168:459–468, 2007.

[20] W. Kempton, V. Udo, K. Huber, K. Komara, S. Letendre, S. Baker, D. Brunner, and N. Pearre. A test of vehicle-to-grid (V2G) for energy storage and frequency

regulation in the PJM system. *Results from an Industry-University Research Partnership*, 2008.

[21] Energy Networks Association. Distributed generation connection guide: a guide for connecting generation that falls under G83/1-1 stage 1 to the distribution network. Version 3.3, November 2011.

[22] Energy Networks Association. Distributed generation connection guide: a guide for connecting generation that falls under G59/2 to the distribution network. Version 3.3, November 2011.

[23] W. Kempton and T. Kubo. Electric-drive vehicles for peak power in Japan. *Energy Policy*, 28:9–18, 2000.

[24] H. Turton and F. Moura. Vehicle-to-grid systems for sustainable development: and integrated energy analysis. *Technological Forecasting and Social Change*, 75:1091–1108, 2008.

[25] G. Strbac, M. Aunedi, D. Pudjianto, P. Djapic, F. Teng, A. Sturt, D. Jackravut, R. Sansom, V. Yufit, and N. Brandon. Strategic assessment if the role and value of energy storage systems in the UK low carbon energy future. *Imperial College London publication for Carbon Trust*, June 2012.

[26] H. Lund and W. Kempton. Integration of renewable energy into the transport and electricity sectors through V2G. *Energy Policy*, 36:3578–3587.

[27] E.ON. *Private Conversation with J. Brandt*, October, 2011.

[28] J. Motavalli. Power to the people: Run your house on a prius. *New York Times online*, accessed August 2013. http://www.nytimes.com/2007/09/02/automobiles/02POWER.html.

[29] J. C. Mankins. Technology readiness levels. *NASA White Paper*, 1995.

[30] US Department of Energy. Technology readiness assessment guide DOE G 413.3-4. 2009.

[31] B. Dawson. The impact of technology insertion on organisations HFIDTC/2/12.2.1/1 Version 3. *Human Factors Integration Design Technology Centre*, 2007.

[32] Automotive technology and manufacturing readiness levels: A guide to recognised stages of development within the automotive industry. *Low Carbon Vehicle Partnership publication in association with the Automotive Council*, 2011.

[33] Xcel Energy runs nation's first commercial vehicle-to-grid test in Boulder. *Xcel Energy press release*, accessed August 2013. http://www.xcelenergy.com/About_Us/Energy_News/News_Archive.

[34] EDISON website. accessed September, 2010. http://www.edison-net.dk/.

[35] Pacific Gas and Electric company energizes silicon valley with vehicle-to-grid technology. *PG&E press release*, April, 2007 (accessed 2010).

[36] Google.org launches rechargeIT plug-in hybrid car initiative and unveils solar installation. *Green Car Congress*, accessed August 2013).

[37] D. Leffingwell. *Agile Software Requirements: Lean Requirements Practices for Teams, Programmes and Enterprise.* Pearson, 2011.

[38] Electric Power Research Institute. PEV as storage scenario. *EPRI Use Case Repository*, May, 2009.

[39] H. A. Kiehne *editor*. *Battery technology handbook.* Expert Verlag, 2$^{\text{nd}}$ edition, 2003.

[40] H. L. Willis and W. G. Scott. *Distributed power generation: planning and evaluation.* Marcel Dekker, 2000.

[41] P. Van den Bossche, F. Vergels, J. Van Mierlo, J. Matheys, and W. Van Autenboer. SUBAT: an assessment of sustainable battery technology. *Journal of Power Sources*, 162:913–919, 2006.

[42] C.F. Walker and J.L. Pokoski. Residential load shape modelling based on customer behaviour. *IEEE Trans. on. Power Apparatus and Systems*, 1985.

[43] US Consumer Product Safety Commission. Carbon monoxide questions and answers. *CPSC Document #466.*

[44] G. Sinden. Characteristics of the uk wind resource: long-term patterns and the relationship to uk electricity demand. *Energy Policy*, 35(1):112–127, 2005.

[45] C. Cottrell and J. Jukwey. German renewables output hits record high in H1. *Reuters—Berlin*, retrieved, July 2012. http://www.reuters.com/article/2012/07/26/germany-renewables-idUSL6E8IQIA720120726.

[46] D. J. C. MacKay. *Sustainable Energy—without the hot air.* UIT Cambridge, Available free online from www.withouthotair.com, 2008.

[47] E. Sortomme, G. Mappes, S. Venkata, and B. Foster. Fault analysis and protection of a microgrid. *IEEE Power Symposium*, 2008.