D1.2 – Long-term estimates of V2G opportunities

V2GB Project

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Contents

Executive Summary .................................................................................................................. 1

1. Introduction .......................................................................................................................... 3
   1.1. Project Overview ........................................................................................................... 3
   1.2. Introduction to Work Package 1 .................................................................................. 3

2. Estimating the opportunities for V2G ................................................................................ 5

3. Methodology for analysis ..................................................................................................... 7
   3.1. Background to modelling capability ........................................................................... 7
       3.1.1. Energy system analysis – ESME ........................................................................ 8
       3.1.2. Electricity distribution network analysis – MEDT ............................................ 10
       3.1.3. EV charge point analysis – MCPT ................................................................ 10
       3.1.4. EV analysis – ECCo ....................................................................................... 11
   3.2. Calculation of V2G Capacity ...................................................................................... 11
   3.3. Energy System Scenarios and Vehicle Charging Cases .............................................. 14
       3.3.1. Baseline 2030 scenario (Scenario 1) ................................................................ 14
       3.3.1. High flexibility 2030 scenario (Scenario 2) ....................................................... 14
   3.4. Vehicle Charging Cases ............................................................................................ 14
       3.4.1. V2G Max case and V2G Min case .................................................................... 14
       3.4.2. Unmanaged charging case .............................................................................. 14
       3.4.3. Managed charging case ................................................................................... 15
   3.5. Assumptions ................................................................................................................ 16

4. Analysis results .................................................................................................................... 19
   4.1. V2G results overview ................................................................................................. 19
   4.1.1. Baseline scenario: Unmanaged charging – V2G .................................................... 23
   4.1.2. V2G available capacity sensitivity analysis ........................................................... 32
   4.1.3. Intermittent generation level sensitivity analysis .................................................... 37
   4.1.4. Managed Charging: Baseline scenario – High flexibility scenario ...................... 51

5. Conclusions and Recommendations .................................................................................. 59
   5.1. Summary of results ...................................................................................................... 59
   5.2. Conclusions ................................................................................................................ 61
   5.3. Recommendations ...................................................................................................... 62

6. References ........................................................................................................................... 64

7. Appendix ............................................................................................................................... 65
Long-term estimates of V2G opportunities

7.1. Acronyms ........................................................................................................................................... 65
7.2. Electricity Generation Technologies ................................................................................................. 66
7.3. Renewable energy generation profiles ............................................................................................... 67
7.4. V2G injection and withdrawal graphs – V2G Min case .................................................................... 69
Executive Summary

The Vehicle to Great Britain (V2GB) project has been developed to: understand the long-term value of and short-term opportunities for Vehicle-to-Grid (V2G) in the UK; identify and evaluate business models for deploying V2G; and develop a sustainable routemap for scaling up V2G. Work package 1 (WP1) has investigated the long-term market value and where V2G might be applicable in a wider energy system context. This report summarises the whole energy system analysis undertaken to examine the long-term opportunity for V2G.

The analysis draws on the key drivers and dependencies identified from the literature review and from the sector expertise within the project team; summarised in D1.1 – Key Drivers and Dependencies. The analysis has been carried out using modelling capability licensed to the Energy Systems Catapult and developed in the ETI’s Consumers, Vehicles and Energy Integration (CVEI) project (Energy Technologies Institute, 2018). The modelling capability encapsulates the whole energy system, covering the different forms of energy supply, network infrastructure and end-use sectors, whilst providing a higher level of fidelity for the transport sector. This has been used to support the analysis of how intermittency and demand variability affect the utilisation of V2G out to 2030.

To enable the analysis V2G has been incorporated into a whole energy and transport system modelling capability. This approach has identified some valuable high-level conclusions about the impact of V2G on the whole energy system and the role it can play. The role of V2G was assessed through two main scenarios. In the baseline scenario the energy system in 2030 is modelled with the objective of meeting the UK’s 2050 greenhouse gas emissions targets. The second scenario was a sensitivity analysis around the impact that high generation of intermittent generation will have on the system. Two alternative vehicle charging strategies were also modelled in the same framework. An unmanaged charging case, where it is assumed that V2G is not deployed, and a managed charging case. The two cases were used in the analysis to better assess the impact that V2G had on the energy system. The main conclusions from the modelling work were:

- V2G reduced the requirement for additional grid-connected electricity storage in 2030 and the need to use that storage.
- When V2G was deployed the installed capacity of flexible generation plants, e.g., Combine Cycle Gas Turbines (CCGTs), was reduced. Furthermore, their utilisation was also increased when V2G was deployed.
- There are diminishing returns associated with increased availability of V2G.
- There is the risk that assumed availability of V2G can have unintended consequences associated with increased utilisation of flexible plant and overall supply efficiency. This is exaggerated when generation from wind and solar sources is increased due to the uncertainty around availability of intermittent generation.

With the modelling encompassing the whole energy system, areas where further, more detailed analysis could derive additional insight were identified. The work provides a roadmap for further modelling work. The areas for further work that were identified by the current analysis are:

- Use of more temporally detailed analysis of energy system operation over extended time periods to provide further insight on the key areas of interest.
- Use of dynamic network modelling to investigate the energy flow between V2G and the network.
- Sensitivity analysis around the level of intermittent generation and electrification of non-EV loads.
- Sensitivity analysis around the available capacity of V2G, the impact of varying vehicle battery size on V2G opportunity.
Long-term estimates of V2G opportunities

- Incorporating learnings about mainstream consumer EV usage and charging behaviour and the potential impact on V2G availability
- More granular analysis of fleet utilisation, vehicle battery sizes, battery degradation impacts and charging strategies to inform V2G opportunity amongst different types of fleet.
- Accounting for risk and uncertainty in key supply factors (e.g. short-term wind availability) and vehicle availability factors (e.g. due to journey variations)
- Enhance modelling with data on V2G technology costs to inform business model feasibility assessments

Based on the current analysis the estimation of the market size of the accessible services is covered in D1.3 – Long term estimates of size of V2G market.
1. Introduction

1.1. Project Overview

Widespread deployment of electric vehicles (EVs) could mean the vehicle fleet represents an energy asset of national significance. Studies by partners in this project have shown how EVs can stabilise grids, delay infrastructure investments, increase the deployment of variable renewable energy technologies on grids, reduce curtailment, lower grid carbon emissions, and provide low cost energy for driving, all without interrupting the service provided to the driver. It has been proposed that Vehicle to Grid (V2G) can contribute to system flexibility and help achieve these outcomes and, in doing so, provide additional revenue streams to EV drivers that could boost ULEV sales.

There still remain significant gaps in knowledge on; potential V2G markets and revenue streams; competition with other technologies; driver behaviour and response to V2G; and commercial arrangements and legislative constraints. The V2GB feasibility study will examine these knowledge gaps and provide a sound basis upon which to build the sector. It will:

- **Assess the risk associated with V2G revenues in the long term** -- identifying the key drivers and dependencies for future V2G revenues, and give long term estimates (ranges) of V2G revenues
- **Improve confidence in the availability of revenue streams near-term** -- using high resolution models and detailed vehicle movement datasets to model revenues, portfolio dispatching, and impact of customer behaviour.
- **Identify and evaluate business models for deploying V2G** -- providing recommendations on feasible and efficient business models, overcoming roadblocks and identifying industry enablers
- **Develop a sustainable routemap for scaling up V2G** -- identifying V2G technology cost and performance thresholds and target markets as the sector (and competition) grows.
- **Project reporting and industry dissemination** -- using extensive dissemination routes across transport and energy sectors including Power Responsive, LCNI conference, auto industry.

1.2. Introduction to Work Package 1

Work package 1 (WP1) of the V2GB project has investigated the long-term market opportunity and potential revenues for V2G. The initial questions that need to be answered are; what is the potential size of the market for V2G in the UK? And what factors will influence the size of the market in the UK? The scope of this work package includes the following outputs:

- Examining the potential size of the market in 2030
- Establishing credible energy system compositions for 2030
- Outlining the competing ways in which system flexibility can be provided
- Identifying drivers of V2G market size and value (drawing on existing work where available)

The approach taken within the work package is to use current data and understanding to represent V2G in a whole energy system modelling environment and explore the opportunity for it to be used in the longer term; when there are a significant number of EVs on the road and the wider energy system has a greater need for system balancing. The work package itself has been broken down into three areas:

- Identification of key drivers and dependencies for V2G revenues – through a literature review and drawing on the sector expertise within the project team.
- Establish the long-term opportunity for V2G – through whole energy system analysis incorporating a V2G offering (that reflects EV deployment levels) alongside alternative means of providing flexibility.
- Estimate potential future value of opportunities – through further qualitative assessment of technical considerations, market size and price factors.
The work package is separated into three deliverables. Each deliverable will include a different part of the analysis. The deliverable outputs and the associated tasks within each deliverable are:

**D1.1 – Key drivers and dependencies for future V2G revenues**
- Review of literature on V2G value and system flexibility
- Identification of drivers

**D1.2 – Long term estimates of V2G opportunities**
- Design of energy system scenarios
- Adaptation of model to represent V2G and testing
- Gathering and processing of input data to develop the scenarios for the CVEI tool
- Analysis and processing of output data from the CVEI tool to answer the identified questions

**D1.3 – Long term estimates of size of V2G market**
- Estimation of system flexibility requirements
- Estimation of V2G market potential

The outputs from WP1 will help to support the other deliverables and provide guidance in the areas where V2G has its long-term value. It will also identify which drivers and dependencies are within the scope of this work package and those which could be analysed within other work packages.
2. Estimating the opportunities for V2G

From the literature review a series of “drivers” expected to influence the opportunity and revenues for V2G were identified, alongside alternative means of providing system flexibility with which V2G would be expected to compete. These are summarised in D1.1 – Key drivers and dependencies for future V2G revenues.

The identified drivers of V2G value were categorised into *electricity system factors* (e.g. demand variability) and *vehicle availability factors* (e.g. number of EVs participating in V2G). The recommendations from this work were that in estimating the opportunities for V2G there should be appropriate assessment of these factors. The approach to addressing this has been to undertake whole energy system analysis to examine the opportunity for an aggregate parc of EVs to provide flexibility to the system by representing:

- aggregate availability of V2G storage across the overall EV parc in 2030 accounting for EV deployment and battery capacity, average travel patterns, charging locations, dwell times and charging rates;
- high-level flexibility requirements for the electricity system in 2030 (with the view that V2G may be able to help satisfy some of these) within the overall energy system, accounting for decarbonisation across the energy system;
- variation in flexibility requirements in 2030, during the day, at different times of the year and during extreme periods;
- competing options for providing flexibility to the electricity system in 2030 alongside V2G.

Drawing on V2G data from sector expertise within the project team, it has been possible to represent V2G as described above in a whole energy system (including transport) modelling capability. The modelling capability, described in section 3.1, comprises a series of tools that represent different parts of the energy and transport system. The modelling capability has been applied to credible 2030 energy and transport systems.

The characterisation of these 2030 systems has factored in the deployment required to meet longer term goals in both sectors.

- For transport, this included being on a trajectory to meeting the UK Government’s stated 2040 car and van targets, accounting for turnover rates of the vehicle parc.
- For the UK as whole, this included being on a trajectory to meeting the UK Government’s 2050 greenhouse gas (GHG) emissions targets, accounting for construction rates across energy, buildings and industry and developments in other parts of the transport sector1.

The deployment rates are factored into the period up to 2030 as well; so, deployment rate limits that are inherent in each sector inform the environment in which V2G is operating by that point. When examining 2030, this means that, for example, the age and performance characteristics of the combined transport and energy technologies reflect a realistic mix achievable by that point. For V2G specifically, this enables an assessment of the opportunity for V2G in 2030 in terms of, for example:

- The respective efficiencies and availability of the generating plant (both between and within generation types) on line in 2030;
- The extent of grid-connected electricity storage that could be on the system in 2030;

1 Including heavy goods vehicles, buses, construction vehicles, agricultural vehicles, rail and UK-specific marine and aviation.
The size of EV batteries across the car and van parc including both models that are new in 2030 and older models that are still on the road at that point.

The 2030 systems have also been designed to be self-consistent, so they are generating enough of the right type of energy to meet both transport and wider energy demands by that point. As well as technology deployment constraints, this also factors in the availability of the underlying energy resources. Throughout all of this, the systems are designed to meet 2030 demands for energy and transport, based on Government projections for population changes and underlying evolution of travel, home occupancy, heating, lighting, industry, etc.

To extend the representation of the long-term opportunity for V2G, two overarching scenarios for 2030 have been designed. The distinction between them, based on the findings of the literature review and in discussion with project partners, is the level of flexibility that the energy system requires, achieved by exploring a Baseline 2030 Scenario and contrasting it with a High Flexibility 2030 Scenario with greater intermittent generation on the system. These scenarios have been further sub-divided into four cases each. These cases examine variations in the charging regimes and V2G availability, identified amongst the vehicle availability factors. Whilst analysing the vehicle availability factors is beyond the original scope of WP1, it has been identified as being of additional value to the project as a whole. The scenarios and the cases within each of these are described further in section 3.2.

This analysis lays down a whole system foundation for understanding the long-term opportunity for V2G, when there are more EVs on the road and more renewables on the system. The analysis also helps to identify where to target more detailed analysis to interrogate this opportunity further.

Beyond its stated aims to identify “drivers” expected to influence the opportunity for V2G and competing flexibility providers, the literature review also identified services expected to be most accessible by V2G and specific challenges V2G faces. These and the findings from the analysis are used to inform D1.3 – Long term estimates of the size of the V2G market.
3. Methodology for analysis

To understand the long-term value of implementing V2G in the UK landscape, analysis has been carried out using modelling capability developed in the ETI’s Consumers, Vehicles and Energy Integration (CVEI) project (Energy Technologies Institute, 2018) and licensed to the Energy Systems Catapult. The use of the modelling capability is the starting point for the analysis, with the results generated used to inform the findings that are generated and subsequent iterations using the tools.

This modelling capability encapsulates the whole energy system, covering the different forms of energy supply, network infrastructure and end-use sectors, whilst providing a higher level of fidelity for the transport sector. V2G functionality has been added to the modelling capability and the series of tools it comprises (see section 3.1).

Self-consistent 2030 scenarios and different cases within these have been designed to test the impact of some of the electricity system and vehicle availability factors identified through the literature review on the long-term opportunity for V2G (see section 3.2).

In combination, this allows interrogation of the impact on or from V2G availability in the following areas:

- Electricity generation capacity requirements
- Electricity production from the available generating technologies
- Grid-connected electricity storage requirements
- Electricity distribution network reinforcement requirements
- Variation in flexibility provision across the day and between summer and winter
- Car and van parc configuration

3.1. Background to modelling capability

The modelling capability used within this analysis has been developed to provide an integrated, holistic means of quantifying and qualitatively assessing the impacts on and from infrastructure, consumers, vehicle uptake and use, policy measures and commercial models across the system.

It comprises several individual models with each processing data and then sending this information to the next tool in the sequence. Figure 1 shows a simplified schematic of the tools, their interactions and where key elements of the energy and transport system are represented.

The four main components of the modelling capability that form the basis for the analysis undertaken in this project are:

- ESME (Energy System Modelling Environment) – used for the energy system analysis
- MEDT (Macro Electricity Distribution Tool) – used for the electricity distribution network analysis
- MCPT (Macro Charging Point Tool) – used for the EV charge point analysis
- ECCo (Electric Car Consumer Model) – used for the EV analysis

These are described in more detail in the following sections.
3.1.1. Energy system analysis – ESME

ESME models the UK energy system with sufficient spatial and temporal detail to understand system engineering challenges, for example around building an electricity system that meets demand in different seasons: summer, winter and peak and at different times of the day. The peak day is defined as a case with high energy demand and low generation from wind and solar.

There are 5 different time periods represented within ESME for each season, each representing a certain time of the day. The distribution of hours of the day to each time slice is seen in Table 1.

Table 1: ESME time slice periods

<table>
<thead>
<tr>
<th>Time slice</th>
<th>Time period</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning</td>
<td>06:00 – 10:00</td>
<td>4</td>
</tr>
<tr>
<td>Mid-day</td>
<td>10:00 – 16:00</td>
<td>6</td>
</tr>
<tr>
<td>Early evening</td>
<td>16:00 – 19:00</td>
<td>3</td>
</tr>
<tr>
<td>Late evening</td>
<td>19:00 – 23:00</td>
<td>4</td>
</tr>
<tr>
<td>Overnight</td>
<td>23:00 – 06:00</td>
<td>7</td>
</tr>
</tbody>
</table>
Each season and time slice have a specific energy demand associated with it which needs to be met (Figure 2). This represents the most detailed level of flexibility requirements on the system. The intra-day variation is based on variations in demand and availability of solar power. The overall demand accounts for regional variations, for example heating loads across the UK.

In ESME, all system loads are represented, including across electricity, heat, hot water, transport and industry. Various generation, storage, network and utilisation technologies are deployed in any given analysis. Given the nature of V2G, this analysis has focussed on:

- Electricity generation technologies – including renewable, nuclear and gas generation
- Grid-connected electricity storage – with a range of costs, performance characteristics and applications
- Electricity transmission networks – accounting for both onshore and offshore requirements

The role of the electricity generation technologies is critical to the opportunity for V2G. Within ESME, each technology has its own performance parameters. For electricity generation technologies, parameters\(^2\) include:

- Peak contribution factor – the percentage of capacity that statistically contributes to meeting the peak electricity demand of the year at a 95% confidence level.
- Flexibility factor – the ability of an electricity generation technology either to contribute to meeting fluctuating electricity demand or to place demands for flexibility on the system.

Whilst each technology is analysed using its own specific performance parameters, to aid with the presentation of the results (in section 0), the electricity generation technologies have been classified as:

- Intermittent generation – e.g. onshore wind
- Flexible generation – e.g. open cycle gas turbines
- Generation with low flexibility – e.g. nuclear

\(^2\) The parameters have been calibrated against more temporally detailed dispatch modelling
A list with the full classification of electricity generation technologies can be found in the Appendix in section 0 along with a list of the grid-connected electricity storage technologies included within the analysis.

As indicated in Figure 1, ESME is also where underlying energy resources, wider energy system demands and wider energy system technologies are accounted for. Summaries of what is covered within these are included in Table 2.

**Table 2: Descriptions of other areas covered by ESME as a part of the analysis**

<table>
<thead>
<tr>
<th>Area</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy resources</td>
<td>The underlying energy resources that are available to the UK, covering: solar, hydro, tidal stream, wave, wind, nuclear, geothermal heat, biomass, biomass imports, biofuel imports, liquid fuel, wet waste, gas, coal</td>
</tr>
<tr>
<td>Wider energy system demands</td>
<td>The overall demands the energy system needs to satisfy based on Government projections for population changes and underlying evolution of home occupancy, heating, lighting, industry, etc. This is also where non-car and van transport requirements (including for goods, rail, UK marine, UK aviation and for off-road vehicles) are accounted for.</td>
</tr>
<tr>
<td>Wider energy system technologies</td>
<td>Alongside the electricity sector technologies (generation, storage and transmission), the technologies across the wider energy system necessary to satisfy the energy demands given the available energy resources, including for: domestic and commercial buildings; industry; non-car and van transport; and other energy networks and storage.</td>
</tr>
</tbody>
</table>

### 3.1.2. Electricity distribution network analysis – MEDT

Reinforcement requirements for electricity distribution networks are calculated through the MEDT. The analysis covers a variety of distribution network architectures across UK urban and rural environments.

The reinforcement requirements account for EV deployment and use, as well as wider energy system evolution, notably electrified heating, alongside other domestic, commercial and industrial loads connected at various levels of the distribution network. This factors in time of day requirements, for example, the hourly charging profiles of EVs connected at the different EV charge point locations accounted for in the analysis (see section 3.1.3),

The above is used to determine the required investment to reinforce UK distribution networks to accommodate the combined loads.

### 3.1.3. EV charge point analysis – MCPT

The analysis of EV charge point requirements utilises the MCPT. The analysis has covered charge points across several locations:

- Home charge points – 7 kW assumed charge rate in 2030
- Workplace charge points – 7 kW assumed charge rate in 2030
Long-term estimates of V2G opportunities

- Rapid charge points at charging stations – 50 kW assumed charge rate in 2030
- Public charge points – 7 kW assumed charge rate in 2030

The rate of charge for each charge point location is shown in Table 3. The quantity of charge points deployed is linked to the deployment of EVs (see section 3.1.4), based on expected requirements and capacities at the above locations.

For the V2G scenarios (described in later sections), V2G was assumed only to be available at home and workplace locations, given parking duration periods at other locations providing relatively little opportunity for V2G. Other chargepoints were still available in these scenarios and utilised for providing charge to vehicles.

Table 3: Charge point ratings

<table>
<thead>
<tr>
<th>Location</th>
<th>Installation before 2020</th>
<th>Installation from 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home</td>
<td>3 kW</td>
<td>7 kW</td>
</tr>
<tr>
<td>Work</td>
<td>3 kW</td>
<td>7 kW</td>
</tr>
<tr>
<td>Public</td>
<td>3 kW</td>
<td>7 kW</td>
</tr>
<tr>
<td>Rapid</td>
<td>50 kW</td>
<td>50 kW</td>
</tr>
</tbody>
</table>

3.1.4. EV analysis – ECCo

The analysis of EVs utilises ECCo. Within ECCo a detailed picture of the car and van parc can be examined. The analysis accounts for:

- The number of vehicles on the road, linked to population and travel patterns, across all passenger car and light commercial vehicle categories
- The proportion of each type of powertrain on the road, e.g. BEV and PHEV
- The electric ranges of the different powertrains within each of the vehicle categories
- Travel demands for different types of private and business users
- The energy requirements for the vehicle parc based on the mix of vehicles and associated travel patterns
- Charging profiles at the different charging locations (see section 3.1.3) based on travel patterns associated with different types of users (including parking times) and charge rates at each of the locations

3.2. Calculation of V2G Capacity

The aggregate amount of V2G storage available was calculated from the number of vehicles plugged in, as shown in Figure 3. This calculation was performed for each hour of the day, and a weighted average was used to accommodate the different charging profiles for weekends compared to week days.
The available capacity of V2G was then converted from an hourly representation to one based on ESME time slices. The hour with the highest availability within each time slice was assumed to represent the availability for the entire time slice, and therefore this case is referred to as the V2G Max case. A sensitivity analysis around the available capacity of V2G was performed using the hour with the minimum availability (V2G Min). Whilst analysing the vehicle availability factors is beyond the original scope of WP1, it has been identified as being of additional value to the project as a whole. Figure 4 illustrates the calculation of availabilities for each time slice for the two cases.

During each time slice, the system may inject into or withdraw from the aggregate V2G storage as required, but the net injection/withdrawal may not exceed the amount of V2G available within that time slice. The available V2G capacity would depend on the available vehicles and battery capacity as explained in Figure 13. The state of charge at the end of each time slice carries forward into the next, with vehicles joining the V2G pool replacing any which have left.
Long-term estimates of V2G opportunities

Figure 4: V2G availability profile
3.3. Energy System Scenarios and Vehicle Charging Cases

3.3.1. Baseline 2030 scenario (Scenario 1)

The long-term opportunity for V2G is set in a scenario in which the energy system in 2030 is on track to meet the 2040 ULEV targets that have been set by the UK Government, and is also on a trajectory to achieving the 2050 greenhouse gas emissions targets of an 80% reduction in GHG emissions from 1990 levels. In this scenario there is twice as much generation from renewables in 2030 as in 2015, and 8% of all heating is electrified. This scenario is designed to give an indication of the value of V2G in a wider system context when trying to reach government targets.

3.3.1. High flexibility 2030 scenario (Scenario 2)

As a sensitivity, based on the findings of the literature review and discussions with project partners, a scenario was defined to test the impact of high intermittency and demand variability on the level of V2G that is utilised. In this scenario, the same targets are used as in the baseline, but the installed capacity of wind and solar in 2030 is 18% higher than in the baseline scenario, and there is 20% greater electrification of heat, achieved through a combination of electric resistive heating and heat pumps.

3.4. Vehicle Charging Cases

For the two scenarios defined above, four cases were tested, which examine variations in charging regimes and the availability of V2G.

3.4.1. V2G Max case and V2G Min case

In the V2G case, V2G is available and all consumers and plug-in vehicles participate. All home and workplace charge points are bidirectional. The V2G Max case is the main case, and the V2G Min case is the sensitivity described in section 3.2. In this case, vehicles begin charging when they are plugged in, but do not unplug until they are needed for a journey.

3.4.2. Unmanaged charging case

In this case, the V2G technology is not available. Vehicles begin charging when they are plugged in, and once they finish charging have no further impact on the electricity network. The charging profile in this case is the same as for the V2G cases and is shown in Figure 5.
Long-term estimates of V2G opportunities

Figure 5: Hourly charging demand for the unmanaged charging and the V2G cases

3.4.3. Managed charging case

In this case, a proportion of vehicles on the road are assumed to engage in managed charging, shifting load away from peak times. For the purposes of this study it was assumed that V2G was not available in this case.

The relationship between the scenarios and cases is illustrated in Figure 6, and a summary of the key features and differences between the modelled cases is presented in Table 4.

Figure 6 Scenarios and cases modelled
3.5. Assumptions

The assumptions made, and scope of the modelling and analysis are summarised in Table 5.

Table 5: Model assumptions

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Source / Reason for Assumption</th>
<th>Relevant modelling case</th>
</tr>
</thead>
<tbody>
<tr>
<td>As of 2040, no new ICE vehicles are available</td>
<td>Agreed with project partners to reflect UK Government targets</td>
<td>All</td>
</tr>
<tr>
<td>Vehicle segments A to I and S are included in the model</td>
<td></td>
<td>All</td>
</tr>
<tr>
<td>Fuel Cell Hydrogen Vehicles (FCHV) are not available at any point</td>
<td>Agreed with project partners</td>
<td>All</td>
</tr>
<tr>
<td>All plug in electric vehicles can participate in V2G at all points in the modelled period</td>
<td>This provides an optimistic assumption about the opportunity for V2G, if all vehicle models and home and workplace charge points were to enable this.</td>
<td>V2G</td>
</tr>
<tr>
<td>Vehicles participate in V2G when charging at home or at work</td>
<td>Based on parking durations, these offer the most plausible locations to offer V2G. The rationale behind rapid charging is assumed not to be compatible with V2G</td>
<td>V2G</td>
</tr>
<tr>
<td>Vehicles plug in at 25% state of charge</td>
<td>Based on analysis of charging preferences (Transport for London and Future Thinking, 2015)</td>
<td>All</td>
</tr>
</tbody>
</table>
## Long-term estimates of V2G opportunities

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Source / Reason for Assumption</th>
<th>Relevant modelling case</th>
</tr>
</thead>
<tbody>
<tr>
<td>When a vehicle plugs in, it remains plugged in until it is needed. The length of time varies based on the hour it is plugged in and the location</td>
<td>The length of time is based on analysis of National Travel Survey data (Department for Transport, 2003-2010)</td>
<td>All</td>
</tr>
<tr>
<td>A portion of the vehicle’s nominal battery capacity is assumed to be “unusable”</td>
<td>Based on proprietary automotive battery data licensed to the ESC</td>
<td>All</td>
</tr>
<tr>
<td>1/8 of the vehicle’s usable battery capacity is available for V2G</td>
<td>Nissan guidance that 1/8 of the capacity is the maximum amount of the battery that may be used for V2G within 24 hours to comply with battery warranty conditions</td>
<td>V2G</td>
</tr>
<tr>
<td>The V2G capacity available in a given hour is based on the average battery capacity of vehicles in the parc</td>
<td>Analysis examines the aggregate available V2G storage capacity across millions of vehicles.</td>
<td>V2G</td>
</tr>
<tr>
<td>V2G storage has an efficiency of 91%</td>
<td>Based on assumption that, if required, V2G could match grid-connected li-ion battery storage efficiency</td>
<td>V2G</td>
</tr>
<tr>
<td>The minimum discharge rate of the V2G storage is the rated output of a single charge point</td>
<td>To provide a boundary condition that the lowest supply from V2G, when required, is that of a single connected vehicle within the aggregate pool of available vehicles</td>
<td>V2G</td>
</tr>
<tr>
<td>The maximum discharge rate of the V2G storage is the number of charge points multiplied by the average rate of charging</td>
<td>Maximum supply from V2G constrained by the aggregate pool of available vehicles and rating of the chargepoints they are connected to.</td>
<td>V2G</td>
</tr>
<tr>
<td>Energy resource availability</td>
<td>Overall availability accounts for variations in availability in energy resources, including solar and wind, across the UK.</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>Solar availability varies both within day and between seasons</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wind availability varies between seasons</td>
<td></td>
</tr>
<tr>
<td>V2G is assumed to have no CAPEX or OPEX</td>
<td>This provides an optimistic assumption about the opportunity</td>
<td>V2G</td>
</tr>
</tbody>
</table>
### Assumption Table

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Source / Reason for Assumption</th>
<th>Relevant modelling case</th>
</tr>
</thead>
<tbody>
<tr>
<td>for V2G and provides an assessment based on technical suitability alone.</td>
<td>Data on V2G CAPEX and OPEX was limited and unverified.</td>
<td>V2G</td>
</tr>
<tr>
<td>The difference between weekday and weekend availability is not fully</td>
<td>The more detailed EV analysis which accounts for weekday and weekend variations in travel</td>
<td>V2G</td>
</tr>
<tr>
<td>represented</td>
<td>patterns is combined into a weighted average day for the energy system analysis.</td>
<td></td>
</tr>
</tbody>
</table>
4. Analysis results

This section provides an overview of the results from the modelled cases along with comparisons between certain cases to better understand the effects of V2G on the whole energy system.

In section 4.1.2, the main V2G case, V2G Max, is contrasted with the Unmanaged charging counterfactual to understand the value V2G adds to the system relative to an equivalent situation without any form of managed charging or V2G.

Section 4.1.3, covers a sensitivity around the availability of V2G. Here the V2G Max case is examined alongside the equivalent V2G Min case, to explore the impact of a less optimistic view of V2G availability.

A sensitivity on the energy system side is explored in section 4.1.4. Here the effects of higher levels of intermittent supply on role of V2G are examined by comparing the baseline 2030 energy system scenario with the high flexibility 2030 energy system scenario for the V2G Max charging case.

An equivalent comparison for managed charging in the baseline and high flexibility energy system scenarios is shown in section 4.1.5, to indicate the relative effect for managed charging to help understand how managed charging compares to V2G.

4.1.1. V2G results overview

An overview of the results of the main V2G case, V2G Max, is shown in this section. As described in previous sections V2G is modelled as a part of the whole energy system. The results below show the impact V2G has on the energy system and what its role could be in the future.

In the case where V2G is deployed, 40% of cars and vans are electric vehicles\(^3\) in 2030. Almost all the BEVs and 90% of the PHEVs are cars. The change in the car and van parc from 2015 to 2030 is shown in Figure 7. As stated in the assumptions table, the aggregate battery capacity from the vehicle parc is used in the modelling. In the analysis of the results the storage available through V2G will be referred to as available V2G storage capacity.

---
\(^3\) Either PHEVs or BEVs
The electricity demand increases by 32TWh in 2030, this is the consequence of increased electrification of transport and a slight increase in demand in industry and lighting. Even though there is some increase in the capacity and production from plants with low flexibility, it’s the capacity and generation from renewable energy technologies that has the highest increase (doubling from 2030). Utilisation of flexible plants has doubled in 2030 compared to 2015, 68% compared to 34%. Even though the installed capacity is reduced in 2030, generation from flexible plants is needed by the system to support the generation from renewables and the increase in demand.
Long-term estimates of V2G opportunities

Grid-connected electricity storage is also required by the system to support the increased generation from renewables. In this case V2G is used instead of added installed capacity of storage. When V2G is deployed no additional grid-connected storage is installed. In 2030 the installed capacity of grid connected storage is 21.4 GWh.

The available capacity of V2G in each time slice, calculated as explained in the methodology section, is presented in Figure 10. It is a result of the charging profile of the vehicles and the aggregate available capacity. For the Max case it represents the maximum availability in each time slice.

To explain the behaviour of V2G, both the injection and withdrawal of electricity in each time slice needs to be considered. In some cases, V2G is not used because the available capacity is not there,
i.e. the vehicle is not at the required state of charge or plugged-in. Figure 11 and Figure 12 show both the injection into and withdrawal from V2G for the Max case. In both days (peak and winter) during the overnight periods energy is injected into the aggregated V2G storage. During the summer day, the utilisation of vehicle storage capacity is close to zero; this is a result of low electricity demand.

Figure 11: V2G injection and withdrawal during peak day – Baseline scenario

Figure 12: V2G injection and withdrawal during winter day – Baseline scenario
4.1.2. Baseline scenario: Unmanaged charging – V2G

An overview of the V2G case was shown in the previous section. To be able to draw conclusions regarding the energy system and the impact of V2G, a comparison between the unmanaged case and the V2G case has been made. The same input charging profiles were used for the two cases. The unmanaged case represents a system where charging demand is present and EVs are available but V2G does not materialise.

Even though the same input profiles were used, the percentage of plugged-in vehicles in 2030 is higher in the unmanaged charging case: 43% compared to 39% on average for the V2G case (Figure 13). As the car and van parc is a model output and the calculation is based on a number of variables, e.g. electricity prices the number of plugged-in vehicles can be different amongst scenarios. This has an impact on the electricity consumption between scenarios, as transport electrification is marginally higher in the unmanaged charging case.

![Figure 13: Car and Van parc – Baseline scenario: Unmanaged charging and V2G cases](image)

The differences in the installed electricity generation capacity and annual electricity production between the case where V2G is deployed and when V2G materialises are seen in Figure 14. The installed capacity of plants with low flexibility and intermittent generation sources remain the same in both cases, whereas flexible generation installed capacity is higher in the unmanaged charging case. The same can be seen in the annual electricity production. The electricity generated from flexible plants is higher when V2G is not deployed (Figure 15).
Long-term estimates of V2G opportunities

The impact of V2G on the installed capacity and generation from flexible plants is seen in Figure 16. The installed capacity is higher in the unmanaged charging case by 5GW, generating 2% more energy. Even though the flexible generation installed capacity is higher, the utilisation of the plants is lower when compared to the V2G case.
Long-term estimates of V2G opportunities

Figure 16: Installed electricity generation capacity (top) and annual electricity production (bottom) from flexible plants – Baseline scenario: Unmanaged charging and V2G

Figure 17 shows the contribution of each flexible plant. The system in both cases relies mostly on CCGTs. The installed capacity of flexible generation plants is shown in Figure 17. The annual production from each technology is presented in Figure 18. In the unmanaged charging case, the utilisation factor of CCGT plants is 60% in comparison to the V2G case where it is 67%. CCGT plants generate 181.5 GWh in the unmanaged charging case compared to 177.6 GWh in the V2G case.
Generation from Open Cycle Gast Turbines (OCGTs) is also different between the two cases. The installed electricity generation capacity and annual generation are shown in Figure 19. Generation from OCGTs is reduced by 0.17 GWh in the V2G case.
Figure 19: Installed electricity generation capacity (top) and annual electricity production (bottom) from OCGTs – Baseline scenario: Unmanaged charging and V2G cases

Figure 20 shows the installed capacity and annual generation from flexible plants which are not fuelled by coal or gas. Compared to 2015 it can be observed that biomass plants and oil-fired generation are decommissioned. The only difference that can be seen is in the installed capacity and generation from hydrogen turbines.
In addition, in the V2G case the use and installation of hydrogen turbines is also reduced. Even though for all cases electricity generation from hydrogen turbines, a potential emerging technology in 2030, is low, in the case of V2G this is halved as seen in Figure 21. The utilisation factor increases from 57% in the case of unmanaged charging to 76% for V2G.
It can be concluded from the above that when V2G is participating in the electricity system, flexible generation technologies that are associated with high operational costs and low utilisation factors are being replaced with V2G. A portion of the peaking capacity required is provided by EVs. Furthermore, improved utilisation of existing units could reduce the operational costs of the system.

The generation from V2G and flexible plants in each time slice is shown in Figure 22. The first observation is that V2G is not deployed during the summer day. Since electricity demand is lower during the summer, there is less need for energy storage, therefore V2G is not deployed on the same scale as in peak and winter seasons.
Long-term estimates of V2G opportunities

A closer look in each time slice in which V2G is deployed is taken in Figure 23. In the cases where V2G is providing electricity to the network, generation from flexible plants is reduced, when compared to the unmanaged charging case where only flexible plants and storage are providing peaking power. This also explains the higher installed capacity and low utilisation of flexible plants in the unmanaged charging case. In order to ensure system reliability and availability capacity of flexible plant is being built that is utilised only in days where demand is high and generation from renewables is low (peak day).

![Flexible generation and V2G per time slice](image)

*Figure 23: Flexible generation and V2G in time slices where V2G is used – Baseline scenario: Unmanaged charging, V2G cases*

It was explained in the overview of the V2G case that when V2G is available additional grid-connected electricity storage capacity is not required in 2030 (compared to the installed capacity in 2015). When comparing this to the requirements of storage in the unmanaged case it can be concluded that when V2G is not available, additional grid-connected storage capacity is needed for the system to balance supply and demand. Electricity withdrawal from grid-connected storage in 2030 is reduced by over 75% in the V2G case and the installed capacity is reduced by 50%. (Figure 24)
Long-term estimates of V2G opportunities

The energy supply from grid-connected storage and V2G are shown in Figure 25. In some cases, as in late evening on the peak day, summer and winter morning, V2G is not used.

When comparing the energy withdrawal from grid-connected storage and V2G in each time slice, the same pattern can be seen. In almost all cases V2G displaces use of other storage technologies and provides a larger percentage of the demand compared to the unmanaged charging case. In
the unmanaged case, total contribution from storage (V2G and non-V2G) is lower compared to the V2G case. The peak day represents a day with low generation from renewables and high demand. It can be concluded that since flexible generation capacity is reduced in the V2G case, storage is needed to provide peak demand instead of flexible plants that will be used in the case when V2G is unavailable.

Finally, the effect of V2G on distribution network reinforcement CAPEX is shown in Figure 26. Increased electricity demand in 2021 from sectors other than transport resulted in the increase in the reinforcement investment costs in that year. In 2030 the cumulative CAPEX in the cases where V2G is deployed is reduced by £200 million. The differences in the two systems that were explained above all contribute to the reduction in the network reinforcement CAPEX in 2030.

![Distribution Network Reinforcement CapEx](image)

**Figure 26: Distribution Network Reinforcement CAPEX – Baseline scenario: Unmanaged charging and V2G**

### 4.1.3. V2G available capacity sensitivity analysis

As a sensitivity, an alternative case using the hour in each time slice with the least availability was considered. This reduced availability of V2G case is referred to as V2G Min, and the previously described case as V2G Max. Due to the whole system approach taken, changes to the availability of V2G led in this case to a small (<1%) increase in the number of electric vehicles adopted, and therefore a higher theoretical maximum V2G capacity. As a result, the available V2G capacity in the peak overnight period is higher in the Min scenario than the Max scenario, despite being lower in all other time periods, as shown in Figure 27. The greatest difference in availability is seen in the morning time slices.
As in the Max case, the Min case has no significant utilisation of V2G during summer. The injection and withdrawal for the peak and winter days in the Min case are shown in Figure 28 and Figure 29. When compared, there is less injection and withdrawal in the Min case than in the Max case in most time slices. However, during the peak morning time slice, withdrawal from V2G is higher in the Min case than the Max case. Over the entire course of the day, both injection and withdrawal are lower in the Min case, as shown in Figure 30, since the available capacity in each time slice is lower compared to the Max case.

Figure 27: V2G available capacity in each time slice – Baseline scenario, V2G Max and Min cases

Figure 28: V2G injection and withdrawal during peak day – Baseline scenario: V2G Min case
Long-term estimates of V2G opportunities

To accommodate the lower availability of V2G, the total amount of generation capacity in the Min scenario is greater. The capacity of flexible generation is greater by 1GW. The actual electricity generated reflects this, with an additional 1.5TWh coming from flexible generators in the Min case. The Max case has a higher level of low flexibility capacity and generation, meaning the overall difference between electricity produced is smaller, and in total the difference in electricity produced is only 1.1TWh (0.3 %) between the scenarios. Although small, as can be seen in Figure
Long-term estimates of V2G opportunities

31, this difference does exceed the extra 0.2TWh demand that results from the greater electrification of transport in the Min case.

![Installed electricity generation capacity](image1)

![Annual electricity production](image2)

*Figure 31: Installed electricity generation capacity (top) and annual electricity production (bottom) – Baseline scenario: V2G Max and Min cases*

The amount of installed capacity of other storage does not differ between scenarios in 2030. This suggests that the amount of V2G and storage available even in the Min case satisfies the system’s requirement for storage of electricity. Use of non-V2G storage within each day varies within the scenarios, but the total energy withdrawn from non-V2G storage is slightly higher in the Min case, as shown in Figure 32.
Considered alongside the described small differences in generation, the results appear to confirm that the greatest benefit to the system is in replacing the need for storage, and that although higher levels of V2G may lead to lower requirements for flexible generation, and lower capacity requirements overall, there are diminishing returns as the availability increases. Further analysis would be necessary to consider a wider range of availabilities and determine what capacities are required to yield particular levels of benefit to the system.

The difference in availability of V2G did not have an appreciable effect on the distribution network reinforcement CAPEX as shown in Figure 33, as it also didn’t have a significant effect on the energy system.
4.1.4. Intermittent generation level sensitivity analysis

A sensitivity analysis around the level of intermittent generation was also performed. This examined an increase in generation from intermittent sources and further electrification of space heat and hot water generation. The role of V2G in such a scenario is assessed and compared against the baseline scenario. One of the input assumptions for the high flexibility scenario was the increase in renewable generation. Figure 34 shows the annual production of electricity for each scenario.
In both scenarios annual generation and installed capacity from all intermittent sources has significantly increased in 2030 compared to 2015. When comparing the two scenarios, the annual generation from wind and solar power is 20% greater in scenario 2. (Figure 35)
Long-term estimates of V2G opportunities

![Installed electricity generation capacity](chart1)

![Annual electricity production](chart2)

**Figure 35**: Installed electricity generation capacity (top) and annual electricity production (bottom) from intermittent sources – V2G: Baseline and High flexibility scenarios

The electricity generation has increased in total by 11TWh mainly due to electrification of space heat and hot water generation and other transport sectors (excluding cars and vans). The total generation is shown in Figure 36.
Flexible generation in the high flexibility scenario has reduced by 5%. Figure 37 and Figure 38 show the generation from the different flexible plants. One obvious difference is that hydrogen turbines are not used in scenario 2 since hydrogen is produced from electrolysis and therefore has a higher cost. Electricity generation from coal remains the same but generation from OCGTs is reduced by half. Even though generation from CCGTs is reduced in scenario 2 their utilisation is also reduced from about 68% to 60%. This change is in line with the change in the flexible generation in the unmanaged charging case (Figure 39 and Figure 41), hence it cannot be attributed to the deployment of V2G and is a feature of how the energy system needs to be balanced in a higher intermittency world.

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**Figure 36: Annual electricity production – V2G: Baseline and High flexibility scenarios**

**Figure 37: Annual electricity production by hydrogen, biomass and waste plants – V2G: Baseline and High flexibility scenarios**
Long-term estimates of V2G opportunities

Figure 38: Annual electricity production by coal and gas plants – V2G: Baseline and High flexibility scenarios

Figure 39: Annual electricity production by hydrogen, biomass and waste plants – Unmanaged charging: Baseline and High flexibility scenarios
The increase in demand is shown in Figure 41. Consumption for hydrogen generation has also increased. In this scenario Carbon Capture and Storage (CCS) is not available and as a result hydrogen needs to be generated through electrolysis to limit CO₂ emissions.

Electricity consumption from the car and van parc has reduced in the high flexibility scenario. In this case the number of electric vehicles is reduced compared to the baseline scenario. In the high flexibility scenario there are 333,000 less BEVs and PHEVs. As can be seen in Figure 42, this represents a modest difference relative to overall numbers of BEVs and PHEVs on the road at that point. In 2030, 38% of cars and vans are either BEVs or PHEVs.
Long-term estimates of V2G opportunities

![Number of BEV and PHEV in the cars and van parc](image)

**Figure 42: Number of BEV and PHEV in the car and van parc - V2G: Baseline and high flexibility scenarios**

As the system is relying more on electricity generated from plants with lower availability (wind and solar in this case) and generation from flexible plants is also reduced, storage capacity is required to provide peaking power when needed. This can be validated by comparing the change in the electricity generation mix in the unmanaged charging case, where the installed grid-connected storage capacity is increased by 2GWh (Figure 43). When V2G is deployed the increase in the installed capacity of grid-connected storage is 4GWh (Figure 44).

![Installed capacity of grid-connected electricity storage](image)

**Figure 43: Installed capacity of grid-connected electricity storage - Unmanaged charging: Baseline and high flexibility scenarios**
The use of grid-connected storage and V2G in each time slice for the two scenarios is shown in Figure 45. During the winter day, V2G is not utilised at the same level in the high flexibility scenario as in the baseline scenario. However, in the winter day no generation from grid-connected storage is seen, even though the installed capacity is increased. Any storage that is required by the energy system is provided by the available capacity of V2G.

As explained in the methodology section, the peak day is characterised by high demand and very low generation from renewables, therefore the utilisation of storage is expected to be high. For both scenarios during the peak day the extraction of energy from V2G is at the maximum available capacity since the system demand for peaking power is at its highest level.
Long-term estimates of V2G opportunities

Withdrawal from Storage and V2G per time slice

Figure 45: Withdrawal from grid-connected electricity storage and V2G in all time slices – V2G: Baseline and high flexibility scenarios

During the peak day, demand from flexible plants is high in both scenarios, and they operate at 95% of maximum capacity in all but the overnight period. The difference in generation between the two scenarios is a result of the difference in installed capacity. V2G is also utilised in the peak day in the time slices with high demand, such as early evening. As explained in other sections of the report, during the summer day demand is reduced and solar generation has higher availability compared to the peak and winter days, therefore energy is not extracted from V2G. (Figure 46)
What can be concluded from both Figure 45 and Figure 46 is that withdrawal of energy from V2G in the high flexibility scenario is lower compared to the baseline scenario. Generation from intermittent sources resulted in an increase in demand, that led to a small increase in generation from plants with low flexibility, e.g. nuclear plants. It would be expected that utilisation of V2G would also be increased in this case as V2G can provide peak energy demand and replace storage.

To examine this behaviour of V2G both the injection and withdrawal of energy from it must be analysed. Figure 47 and Figure 48 show the injection and withdrawal from V2G in the peak and winter days. Linking the injection and withdrawal of V2G in the high flexibility scenario to injection and withdrawal in the baseline scenario, conclusions can be made for the use of V2G when generation from intermittent sources is increased.
During the peak day when comparing the use of V2G in both the baseline and high flexibility scenarios, similar behaviour can be seen (Figure 49). Injection and withdrawal are at the same level, with V2G in the high flexibility getting 0.5GWh more energy from the grid in the overnight period. During the day, in the high flexibility scenario (scenario 2) withdrawal is also slightly higher, from 1 GWh in the early evening period to 0.5GWh in the mid-day period.
In the winter day the injection to V2G is very different between the scenarios (Figure 50). In the baseline scenario 36GWh are injected into V2G, whilst in the high flexibility scenario only 7.8GWh are injected. This will then influence the available energy withdrawn from V2G during the day. As less energy is stored, V2G will provide less energy to the grid during the day.

Since this behaviour is not seen in the peak day, where generation from intermittent sources is minimal, or in the baseline scenario results, the lack of energy injected to V2G in the winter day can be directly linked to the increased levels of intermittent generation in the high flexibility scenario. Solar power is not available overnight and flexible generation is reduced overall in the high flexibility scenario, more specifically in the overnight period it is reduced by 35%. Therefore, there is no available energy to fully charge and utilise V2G in the winter overnight period, which leads to reduced utilisation during the day. Further, grid-connected storage is also not utilised in the high flexibility scenario in the winter day. Injection to grid-connected storage is close to zero and from Figure 45 it was seen that there is no withdrawal from grid-connected storage in the winter day.

![V2G Injection and withdrawal](image)

*Figure 49: V2G injection and withdrawal during peak day – Baseline and high flexibility scenarios*
Regarding the cumulative distribution network investment costs, Figure 51 shows an increase in the high flexibility scenario (scenario 2) of about 80%. There are several factors that contribute to this, not only the lack of V2G participation in the energy generation system. For example, there is increased demand on the electricity system in scenario 2, including from greater electrification of heating. A comparison of the baseline and high flexibility scenarios with the unmanaged charging case supports this, as the cumulative CAPEX is increasing in the high flexibility scenario there as well (Figure 52).
Long-term estimates of V2G opportunities

Figure 51: Distribution Network Reinforcement CAPEX – V2G: Baseline and High flexibility scenarios

Figure 52: Distribution Network Reinforcement CAPEX – Unmanaged charging: Baseline and High flexibility scenarios
4.1.5. Managed Charging: Baseline scenario – High flexibility scenario

In the managed charging case different charging demand profiles have been used. Managed charging is assumed to be taking place at home (Figure 53).

Regarding the managed charging cases some conclusions can be drawn when comparing the results of the two scenarios. The differences in the energy system reflect the scenario differences and those differences can be used to compare the managed case results to the V2G case. A direct comparison would not be appropriate as the two cases rely on different input assumptions in key areas.
Figure 54: Installed electricity generation capacity (top) and annual electricity production (bottom) – Managed charging case: Baseline (scenario 1) and High flexibility (scenario 2) scenarios

Figure 54 shows the electricity generation capacity and energy output in the two scenarios. In both scenarios when comparing the energy generation capacity and output between 2015 and 2030 the same trend is seen. Flexible generation is reduced and renewable sources are increased as well as baseload generation. In both cases electricity demand is increased in 2030, mostly due to electrification of transport.

The vehicle parc that is participating in managed charging for both scenarios is shown in Figure 55. The vehicle parc remains the same for the managed case in 2030, with 45% of vehicles being BEVs or PHEVs participating in managed charging.
One of the input assumptions of the high flexibility scenario is the increased capacity and generation from renewable sources. In the managed case in 2030, renewable generation was increased by 20% in scenario 2 (High flexibility scenario), baseload generation increased by 4% and flexible generation decreased by 6% when compared to scenario 1. (Figure 56).
Electricity consumption in 2030 in scenario 2 was 3% greater compared to scenario 1. It was explained in the methodology section that heat and hot water electrification is higher in scenario 2. For the managed case it is increased from 8.7% in scenario 1 to 10% in scenario 2. Further to that, as CCS is not available in scenario 2 all hydrogen demand is generated through electrolysis. A small increase in electricity consumption is observed for the transport sector, excluding the car and van parc. This can again be linked to the availability of CCS. As carbon capture is not an option further decarbonisation of the demand is required (Figure 57).

The flexible generation is compared in more detail in Figure 58 and Figure 59. Even though all flexible plants are generating less electricity in scenario 2, their utilisation levels are the same as in scenario 1. Generation from CCGTs is reduced by 11TWh. As expected there is no generation from hydrogen turbines and generation from OCGTs is reduced by 32%.
Long-term estimates of V2G opportunities

As flexible generation is reduced but installed capacity of renewables and electricity demand are increased, the electricity system in scenario 2 in the managed case would require additional capacity of storage to cope with the intermittent nature of renewables. The total installed storage capacity in the managed case has increased by 5.5 GWh in scenario 2. The additional capacity is coming from installation of grid-connected batteries and some additional capacity of compressed air and pumped storage (Figure 60).
Long-term estimates of V2G opportunities

![Graph showing installed capacity of grid-connected electricity storage](image)

**Figure 60: Installed capacity of grid-connected electricity storage – Managed charging case: Baseline (scenario 1) and High flexibility (scenario 2) scenarios**

The storage withdrawal in each time slice is shown in Figure 61. In time slices when demand is expected to be high, grid-connected storage is supplying more energy in scenario 2. When managed charging is deployed grid-connected storage is not utilised in the winter day. As in all other cases, during summer the need for grid-connected storage is significantly reduced and during the overnight periods. (Figure 61)

![Graph showing withdrawal from storage per time slice](image)

**Figure 61: Withdrawal from grid-connected electricity storage per time slice – Managed charging case: Baseline (scenario 1) and High flexibility (scenario 2) scenarios**
The impact of the differences between the two scenarios can also be seen in the cumulative reinforcement costs for the distribution network (Figure 62). The high generation of renewables and increase in electrification of transport and generation of heat and hot water increases the investment costs by £250m.

![Distribution Network Reinforcement CapEx](image)

*Figure 62: Distribution Network Reinforcement CAPEX – Managed charging case: Baseline (scenario 1) and High flexibility (scenario 2) scenarios*

When comparing the above to the equivalent comparison for the V2G scenarios, the same system behaviour can be observed. In both cases in the high flexibility scenario, the increase in renewables and the increased electrification of demand are having a similar effect on the energy system. In both cases storage utilisation is lower, baseload generation capacity is increased and installed capacity of flexible plants is reduced. Even though grid-connected storage is not used in the V2G cases, V2G is still being used to supply energy in the winter day. In the early evening time slice in scenario 2, when grid-connected storage withdrawal is at the highest level in the managed charging case, the deployment of V2G reduces the need for grid-connected storage. The morning time slice in the peak day is another example of when V2G is supplanting grid-connected storage.

Moreover, in both cases in the high flexibility scenario energy demand is increased, as a result of the electrification of space heat and hot water generation. Even though the generation from flexible plants is reduced in the high flexibility scenario for both cases there is a difference in how they operate. For the managed charging case, the utilisation factor remains the same in both scenarios, whereas for the V2G cases it drops in the high flexibility scenario.

This might give an indication of how the use of V2G affects the system availability. Even though the installed capacity of flexible generation is reduced in both cases, the difference in capacity is
greater in the managed charging case (11% compared to 7.2%). Moreover, supply from grid-connected storage and the installed capacity grid-connected storage are not increasing as much between scenarios in the V2G case as in the managed charging case, since V2G is catering to some of the demand. In addition to that, V2G utilisation also drops in the high flexibility scenario. This could lead to the conclusion that as energy coming from V2G is reduced, and the other grid-connected storage capacity is not able to cover the demand, the system would need the additional capacity of flexible plants to provide peaking power at days and time slices when demand is high. This would lead to a reduction in utilisation factor.

The investment cost for the distribution network reinforcement are increasing in scenario 2 for both cases, even though the increase in the V2G case is higher by about 20%.
5. Conclusions and Recommendations

5.1. Summary of results

A summary of the key results of the analysis is shown in Error! Not a valid bookmark self-reference.. The table follows the same structure as the analysis in section 4. The charging mode impact on flexible generation, grid connected storage and distribution network investment costs is presented.

**Table 6: Results summary**

<table>
<thead>
<tr>
<th>flexible Generation</th>
<th>Grid connected electricity storage</th>
<th>Distribution network investment costs</th>
<th>V2G</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline scenario: Unmanaged charging – V2G</strong></td>
<td>In the V2G case installed capacity and annual electricity generation from flexible sources were reduced (5GW less capacity was installed generating 2% less electricity). Furthermore, the utilisation of the installed flexible generation plants was increased. CCGT, OCGT and H₂ turbine plants were predominately used to cover the additional demand from flexible plants in the unmanaged charging case.</td>
<td>When V2G is utilised, grid connected storage requirement is reduced. Generation from grid connected storage when compared to the unmanaged charging case was reduced to about half. Electricity withdrawal from grid-connected storage in 2030 was reduced by over 75% in the V2G case. Grid connected storage is utilised in the V2G case only in the “peak day”.</td>
<td>In 2030 the cumulative CAPEX in the cases where V2G is deployed is reduced by £200 million. V2G was used to provide flexible supply to the system during morning, mid-day and early evening periods. Utilisation of V2G resulted in reduced installed capacity of flexible generators and grid connected storage.</td>
</tr>
<tr>
<td><strong>V2G available capacity sensitivity analysis</strong></td>
<td>Increased V2G capacity did not result in a proportional increase in benefit for the system.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>V2G: Baseline scenario – High</strong></td>
<td>Installed capacity of flexible generation was reduced when</td>
<td>The increased generation from intermittent sources resulted in</td>
<td>The cumulative CAPEX was increased in the high flexibility</td>
</tr>
</tbody>
</table>
Long-term estimates of V2G opportunities

<table>
<thead>
<tr>
<th>Flexible Generation</th>
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<tbody>
<tr>
<td><strong>flexibility scenario</strong> (Intermittent generation level sensitivity)</td>
<td>generation from intermittent sources was increased. Generation from flexible plants was reduced by 5%.</td>
<td>increased installed capacity of grid connected storage (4GWh more in the high flexibility scenario)</td>
<td>scenario for both the unmanaged charging and the V2G cases. (~80% increase for the V2G case) This indicates that not only the lack of V2G participation in the energy generation system contributed to this.</td>
</tr>
<tr>
<td>Managed charging: Baseline scenario – High flexibility scenario</td>
<td>Generation from flexible plants was reduced by 6% in the high flexibility scenario relative to the other two charging cases. The utilisation of flexible plant remained the same in both scenarios for the managed charging case. Even though the installed capacity of flexible generation is reduced in both the managed charging and V2G cases, the difference in capacity is greater in the managed charging case (11% compared to 7.2%).</td>
<td>As flexible generation is reduced but installed capacity of renewables and electricity demand are increased, the electricity system in the high flexibility scenario would require additional installed capacity of storage to cope with the intermittent nature of renewables (5.5GWh more in the high flexibility scenario). Supply from grid-connected storage and the installed capacity of grid-connected storage are not increasing as much between scenarios in the V2G case as in the managed charging case, since V2G is catering to some of the demand.</td>
<td>As in the unmanaged charging and V2G cases the distribution network investment costs were increased in the high flexibility scenario (by about 50%).</td>
</tr>
</tbody>
</table>
5.2. Conclusions

The aim of the analysis has been to show the impact of V2G on the energy system. The analysis focused on comparing flexible generation, grid-connected electricity storage, network reinforcement investment costs, electrification of demand and intermittent energy generation.

V2G was compared to an unmanaged charging counterfactual, with equivalent levels of intermittent generation and similar numbers of BEVs and PHEVs, with the same travel demand profiles. The major differences occur between the level of flexible generation that is required, and how it is utilised, and similarly the amount of grid-connected electricity storage that is required and how it is utilised. With V2G available, the amount of flexible generation that needs to be built is reduced. Whilst the amount of electricity that is supplied from flexible generation reduces as well, it does not do so by the same extent and the utilisation of the flexible generation that is built increases.

There is also less grid-connected electricity storage needed when V2G is available, since the aggregate vehicle battery capacity is used instead. This conclusion needs to be considered in the context of the assumptions used. For example, the costs and efficiencies assumed take an optimistic view for V2G given the data available. Specifically, no additional costs were assumed for V2G being available and V2G was assumed to be as efficient as the most efficient grid-connected electricity storage technology, i.e. grid-scale Li-ion batteries.

Beyond the above, the availability of V2G resulted in reduced distribution network reinforcement CAPEX.

The first of the sensitivity analyses centred on the available capacity of V2G. Between these cases, the impact on flexible generation and grid-connected storage capacity and utilisation was minor and the change in the distribution network reinforcement CAPEX was negligible. Increased V2G capacity therefore, did not result in a proportional increase in benefit for the system.

Assessing the impact of greater intermittency on the system on the role for V2G, highlighted some interesting phenomena that would require more detailed assessment. The analysis indicated there was a risk that if V2G capacity is assumed to be available, pushing out alternative means of capacity provision, unintended consequences could result; without a clear understanding of the variability in availability of intermittent generation. For example, the risk that the available flexible plant needs to be used to fill reserved V2G storage during periods of low wind availability overnight, so as to allow the system to still meet peaks in subsequent periods. The result being that the associated round-trip efficiency, from the additional use of the V2G storage, would push up CO₂ emissions more than if equivalent additional flexible generation capacity was being used to supply loads directly. Crucial to understanding the risk associated with this is to examine the uncertainty of variations in availability of generation from intermittent sources from day to day and year to year.

As with the baseline case, the availability of V2G when there is more intermittent generation and increased electrification of heat, restricts the opportunity for grid-connected electricity storage.

Examining equivalent energy system comparisons for managed charging revealed that whilst many of the effects were consistent, i.e. the availability of each option: reduces generation capacity requirements, increases utilisation of certain plant, reduces the need for grid-connected electricity storage and reduces network reinforcement, there were notable differences. For instance, with managed charging, flexible plant utilisation did not increase to the same extent and the effect on grid-connected electricity storage was less pronounced.

Based on assumptions made and the cases modelled the main conclusions of the analysis are summarised here:
Long-term estimates of V2G opportunities

- V2G reduced the requirement to install additional grid-connected storage capacity and the supply of electricity from storage
- The required capacity of flexible generation reduces with the availability of V2G, however, the utilisation of those plants that are built would be expected to increase
- Compared to when V2G is not deployed, investment costs associated with distribution network reinforcement are reduced
- There are diminishing returns associated with increased availability of V2G
- There is the risk that assumed availability of V2G can have unintended consequences associated with increased utilisation of flexible plant and overall supply efficiency. This is exaggerated when generation from wind and solar sources is increased due to the uncertainty around availability of intermittent generation.

5.3. Recommendations

The modelling work undertaken in work package 1 had the objective of providing a high-level analysis of the benefits of V2G to the energy system. Based on the modelling results a series of recommendations can be made for future work.

A representation of V2G has been integrated into a “whole energy system” modelling capability to show how a bidirectional exchange of energy between vehicles and the grid will affect the generation of and demand for electricity; and electrification of other sectors like heat and hot water. This analysis was necessary to be able to see the role that V2G will have in the system and identify areas to focus future modelling and analysis on.

For example, it was shown through the results of the analysis that V2G has a clear advantage when compared to following an unmanaged charging strategy, but in the scenario where the penetration of renewable energy is higher the contribution from V2G was reduced.

As the objective was to identify the potential impact of V2G a lot of the input assumptions were set to be more optimistic or simplified. For example, no additional costs were attributed to the provision of V2G, interconnectors were assumed to make no net contribution to energy supply and only a single charging profile covering both weekend and week days was used in the energy system portion of the analysis.

From the current modelling work the times of the day where V2G is contributing to the energy system and it is adding value were identified. It is recommended that more temporally granular modelling within these key time periods could reveal further insight into how V2G can be utilised.

Detailed dynamic network modelling could also be used to model the interaction of V2G capacity with the network. For example, a dynamic model that will evaluate the role of V2G in a specific location, will be able to model vehicles as an individual storage capacity or will be able to place the storage capacity through V2G in the same geographic location as the demand.

It was concluded from the modelling results, that the penetration of renewables affects the role of V2G in the system as well as the electrification of non-EV loads. It is proposed that future modelling work focuses on sensitivity analysis around generation from renewable energy sources and variation in non-EV loads. Moreover, it was concluded that when generation from wind and solar power is low in the peak day and overnight period, flexible generators can be used to charge reserved V2G capacity. The risk and uncertainty around availability of intermittent supply needs to be examined further to understand the potential severity of insufficient non-V2G capacity provision.
Another recommendation for future work will be a sensitivity analysis around the available capacity of V2G. In the current work all EVs were assumed to be V2G capable and results up to 2030 were analysed as agreed with the project team. The modelling results showed diminishing returns from the increased availability of V2G capacity. A sensitivity around the available V2G capacity and the impact of vehicle battery size will be able to give further information about the capabilities of V2G and indicate at what level V2G starts having an impact on the system.

Finally, as consumer behaviour and choice around V2G is not documented in the literature, an analysis around vehicle use and charging behaviour would be essential. Inputs from this analysis could be then fed back into the current modelling capability. Information that would have an effect on results would be user uptake of V2G capable vehicles, user’s willingness to participate in V2G and charging behaviour.

Additional costs associated with V2G, e.g. to the vehicle and/or the charging system could be added to the modelling capability.

More detailed analysis around fleet utilisation and charging strategies will provide insights on the V2G opportunity in different types of fleet. Vehicle availability factors (e.g. due to journey variations) will also need to be considered.

As detailed analysis focusses on segments of the system, appropriate data will be of high importance. Moving from multi-hour time periods to hourly dispatch modelling to dynamic modelling, where data per second is required, needs the quality and accuracy of inputs to be ensured.

Data will need to cover electricity generation and consumption, charging demand and battery size, vehicle battery State-of-Charge, vehicle battery performance curves, battery charging profiles, the impact of battery degradation, vehicle parc developments and V2G related charging and vehicle system costs alongside consumer behaviour data as explained above.

To be able to inform business model feasibility analysis the current modelling capability can be enhanced with reliable data on V2G technology costs.

The current analysis incorporated V2G charging into a whole energy system modelling capability. The analysis showed that when V2G is adopted the system is affected and various benefits and risks have been identified. The analysis has also identified a number of areas to target future modelling and analysis to build on the findings here.
6. References


7. Appendix

7.1. Acronyms

BaU  Business as Usual
BEV  Battery Electric Vehicle
CAPEX  Capital Expenditure
CCGT  Combined Cycle Gas Turbine
CCS  Carbon Capture and Storage
CVEI  Consumer, Vehicles and Energy Integration
ECCo  Overview of Electric Car Consumer
ESC  Energy Systems Catapult
ESME  Energy System Modelling Environment
FCHV  Fuel Cell Hydrogen Vehicle
GHG  Greenhouse Gas
ICE  Internal Combustion Engine
MCPT  Macro Charging Point Tool
MEDT  Macro Electricity Distribution Tool
NTS  National Travel Survey
OCGT  Open Cycle Gas Turbine
OPEX  Operational Expenditure
PHEV  Plug-in Hybrid Electric Vehicle
ULEV  Ultra Low Emissions Vehicle
V2G  Vehicle to Grid
### 7.2. Electricity Generation Technologies

<table>
<thead>
<tr>
<th>Intermittent generation</th>
<th>Flexible generation</th>
<th>Generation with low flexibility</th>
<th>Storage technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro Wind</td>
<td>Biomass Fired Generation</td>
<td>Biomass Macro CHP</td>
<td>Battery - Li-ion</td>
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<tr>
<td>Offshore Wind (fixed)</td>
<td>Converted Biomass Plant</td>
<td>Gas Macro CHP</td>
<td>Battery - NaS</td>
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<tr>
<td>Offshore Wind (floating)</td>
<td>OCGT</td>
<td>Micro CHP - Hot Water</td>
<td>Compressed Air Storage of Electricity</td>
</tr>
<tr>
<td>Onshore Wind</td>
<td>CCGT</td>
<td>Micro CHP - Space Heat</td>
<td>Flow battery - Redox</td>
</tr>
<tr>
<td>Wave Power</td>
<td>H2 Turbine</td>
<td>Anaerobic Digestion CHP Plant</td>
<td>Flow battery - Zn-Br</td>
</tr>
<tr>
<td>Tidal Range</td>
<td>Oil Fired Generation</td>
<td>Nuclear (Gen III)</td>
<td>Pumped Storage of Electricity</td>
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<tr>
<td>Tidal Stream</td>
<td>IGCC Coal</td>
<td>Nuclear (Gen IV)</td>
<td>V2G</td>
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<tr>
<td>Large Scale Ground Mounted Solar PV</td>
<td>PC Coal</td>
<td>Nuclear (Legacy)</td>
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<tr>
<td>Micro Solar PV</td>
<td>Incineration of Waste</td>
<td>Nuclear (SMR)</td>
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<td>IGCC Biomass with CCS</td>
<td>PC Coal with CCS</td>
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<td></td>
<td>IGCC Coal with CCS</td>
<td>CCGT with CCS</td>
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<td>Hydro Power</td>
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<td>Geothermal Plant (EGS) Electricity &amp; Heat</td>
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<td></td>
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<td>Geothermal Plant (HSA) Electricity &amp; Heat</td>
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</table>
7.3. Renewable energy generation profiles

Wind power generation is assumed to be constant within each season and time slice. A different availability factor is applied for each day, higher for winter and lower for summer. For onshore wind availability also varies by region as well. Solar power generation is assumed to be constant within each time slice. The availability factor varies by region, season and time slice.

![Wind power output](image1)

*Figure 63: Wind power output and installed capacity – Baseline scenario*

![Wind power output](image2)

*Figure 64: Wind power output and installed capacity – High flexibility scenario*
Long-term estimates of V2G opportunities

**Figure 65**: Solar power output and installed capacity – Baseline scenario

**Figure 66**: Solar power output and installed capacity – High flexibility scenario
7.4. V2G injection and withdrawal graphs – V2G Min case

**Figure 67: Baseline scenario, Peak day**

**Figure 68: Baseline scenario, Winter day**
Long-term estimates of V2G opportunities

Figure 69: High flexibility scenario, Peak day

Figure 70: High flexibility scenario, Winter day