



V2G Dynamic Headroom Control

NIA Closedown Report

June 2024 – January 2026

**Electricity
Distribution**

nationalgrid

1.1 Version Control

Issue	Date
0.1	16/12/2025
0.2	18/01/2026
0.3	29/01/2026
Final	27/02/2026

1.2 Publication Control

Name	Role
Liza Troshka and Andrew Urquhart	Author
Geoff Down	Reviewer
Geoff Down	Approver

Contact Details

For further information, please contact:

nged.innovation@nationalgrid.co.uk

Postal

Innovation Team
National Grid Electricity Distribution
Pegasus Business Park
Herald Way
Castle Donington
Derbyshire DE74 2TU

Disclaimer

Neither National Grid, nor any person acting on its behalf, makes any warranty, express or implied, with respect to the use of any information, method or process disclosed in this document or that such use may not infringe the rights of any third party or assumes any liabilities with respect to the use of, or for damage resulting in any way from the use of, any information, apparatus, method or process disclosed in the document.

National Grid 2026

Contains OS data © Crown copyright and database right 2026 No part of this publication may be reproduced, stored in a retrieval system or transmitted, in any form or by any means electronic, mechanical, photocopying, recording or otherwise, without the written permission of the Innovation Manager, who can be contacted at the addresses given above

Contents

Contents	2
1. Executive Summary	3
2. Project Background	4
3. Scope and Objectives	6
4. Success Criteria	7
5. Details of the Work Carried Out	8
6. Performance Compared to Original Aims, Objectives and Success Criteria	18
7. Required Modifications to the Planned Approach during the Course of the Project	20
8. Project Costs	21
9. Lessons Learnt for Future Projects and outcomes	22
10. The Outcomes of the Project	29
11. Data Access Details	31
12. Foreground IPR	32
13. Planned Implementation	33
14. Contact	34
15. Glossary	35

1. Executive Summary

V2G Dynamic Headroom control project is a project led by National Grid Electricity Distribution in collaboration with Loughborough University. The project was commissioned to get a better understanding whether and how dynamic local control of active and reactive powers of Vehicle-2-Grid (V2G) within low voltage (LV) networks can help facilitate accommodation of all Low Carbon Technologies (LCT)s, benefiting local customers and providing increased flexibility services to system operators, while minimising reinforcement costs and optimising fairness between customers.

The project was funded via Network Innovation Allowance (NIA) and involved conducting a desktop simulation research focusing on V2G technology and using smart meter data to:

- Provide improved visibility of the existing capacity headroom along the length of Low Voltage (LV) feeders, and
- Improve the targeting in location and time of active and reactive power management of V2G, (also known as Volt/Var or Volt/Watt control techniques), while improving the confidence that assets will remain within thermal and voltage limits when the uptake of V2G picks up according to DFES2024.

The results of the simulation studies that included 86 National Grid Electricity Distribution (NGED) substations indicated that:

- There is 43% probability level of over-voltage when V2G export added to the model and when no control is implemented; the over-load probability for the same scenario is 13%;
- Volt-watt control appears to be effective in resolving the voltage and current issues, but reduces overall exports level.
- Volt-var control partially reduces over-voltage but increases risk of overloads whilst maintaining the export power.
- Volt-watt thresholds may need to be lower than the regulatory voltage limits to ensure exports do not exceed thermal ratings, and to allow for voltage rise caused by LCTs that export without controls.

Simulation results confirmed that customers at feeder ends would potentially be more constrained due to the higher voltage rise. Fairer approaches are possible but would cause mean export volumes to be reduced. The results also confirmed that V2G exports would increase losses but would provide a valuable energy storage facility.

The results of the study are considered for the follow-up trial where the implementation benefits and risks would be considered and evaluated in greater detail.

The project total cost was £358,217 which was delivered over a period of 18 months with no significant changes to the original project plan, budget or the end date.

2. Project Background

Dynamic and local control of active and reactive powers of Vehicle-2-Grid (V2G) within LV networks can help facilitate accommodation of all Low Carbon Technologies (LCTs), benefiting local customers and providing increased flexibility services to system operators, while minimising reinforcement costs and optimising fairness between customers. There is however a concern that V2G connections can increase levels of power exports, potentially pushing voltages beyond statutory limits and/or exceeding thermal limits. These exports could have long time durations and could have low levels of diversity.

Simple active power export limiting has been trialled previously but risks limiting the very benefits V2G can provide. Methods responding to voltage variations could reduce this risk but pre-configured characteristics could still be far from optimum. Control of V2G reactive power consumption can address local voltage concerns but may not provide compliance with thermal limits. There is a further risk that customers at the ends of feeders will be unfairly affected by these methods.

V2G exports could cause excessive voltage rise, or thermal overloads, for example when multiple customers on the same LV feeder have an aggregated response to provide power for grid support services. The timing of these exports could coincide with daytime periods when exports from domestic solar PV are already high. The rated powers of EV chargers will mostly be greater than those of the solar PV systems, and durations of export could be lengthy where batteries are fully charged, possibly creating high levels of phase unbalance. The timing of V2G exports may also be less diversified than the corresponding imports for EV charging if multiple customers on an LV feeder are responding to the same high-value price signals from an aggregator. V2G exports could therefore have a significant impact on voltage ranges and on thermal loading.

The previous NGED's Electric Nation project addressed these concerns by setting fixed limits to the V2G active power exports. However, in many instances, exports will occur at the same time as other demands, or when other customers cannot participate as their EVs are elsewhere, and so the fixed limit unnecessarily obstructs a potentially useful grid service. The customer may also lose revenue that would have supported their investment in providing the V2G capability.

It seems likely that exports from an EV charger may often operate in a vehicle-to-home (V2H) mode, using charge stored at off-peak times or from periods when solar PV generation exceeded demand, to reduce the need for power imports when electricity prices are higher. This V2H function reduces the customer impact on grid capacity and could improve the financial viability of domestic solar PV systems. A key requirement is therefore to ensure that V2H operation should not be constrained due to the technical possibility that the EV charger could also operate in V2G mode, even if this is not the mode of operation adopted by the customer.

Trials by South Australia Power Networks have adopted voltage-controlled techniques, classified as volt/var or volt/watt characteristics^{1 2 3}. The volt/watt approach reduces the active power exports dynamically at each device according to the measured local voltage. This approach could be effective in avoiding excessive voltage rise and avoids applying the constraint when the voltage ranges are otherwise acceptable. However, it is not guaranteed that the combined exports will also

¹ UNSW Sydney, Curtailment and Network Voltage Analysis Study (CANVAS), https://www.ceem.unsw.edu.au/sites/default/files/documents/CANVAS-Succinct-Final-Report_11.11.21.pdf

² EA Technology, DER and LV management: Finding the least-cost strategy, South Australia Power Networks <https://eatechnology.com/media/nsihkwrdr/aus-case-study-sapn.pdf>

³ [Energy Networks Australia](#)

be within the thermal limits of the feeder cable or substation, and the success of the control strategy depends on the participation of all devices with an export capability. A further concern is that the constraints will mostly be applied to customers at the ends of feeders. These customers will have fewer opportunities to make financial gains from exported power than their neighbours with connections closer to the substation.

The alternative volt/var method requires that the V2G inverters import reactive power to reduce the local voltage, counteracting the voltage rise caused by active power exports. As with the volt/watt scheme, this approach does not guarantee that the exports will remain within thermal limits, and heating due to losses will be increased by the additional currents to supply the reactive power.

These two approaches are designed such that the control policy at the V2G inverters can be pre-configured with each device then operating autonomously thereafter. One of the V2G Dynamic Headroom Controls project objectives was to get a better understanding whether these control policies will achieve the desired objectives with UK LV feeder topologies, or whether the control parameters may need to be modified, either to ensure voltage limits are maintained or to avoid excessive export power constraints. The project also specified an objective to determine how the available export power will be constrained, and how the impact of these constraints will be shared between the customers.

3. Scope and Objectives

Project objectives are listed in the table below.

Table 3-1: Status of project objectives

Objective	Status
Evaluate V2G control techniques to understand their effectiveness in maintaining LV assets within operational ranges in a desk-top environment	✓
Assess the benefits of new techniques where smart meter data is used to customise V2G control methods, varying either with location, time of day, or as the uptake of LCT appliances progresses	✓
Quantify the impacts on losses of reactive power control techniques	✓
Assess the impact on customers, in terms of the likelihood and equity of power constraints	✓

4. Success Criteria

Table 4-1: Status of project objectives

Success Criteria	Status
A clear understanding of the expected benefits of different V2G control strategies that are the focus of this study, and in particular of the additional value obtained if control parameters are updated locally and dynamically rather than being pre-set equally on all devices. This would lead to the specification of control algorithms that can be assessed in a future trial using real V2G devices on live LV feeders.	✓
A clear understanding of the optimum level of control interaction, where improvements in power exports and customer experience fairness are balanced against increased communication overhead.	✓

5. Details of the Work Carried Out

The delivery of V2G Dynamic Headroom Control was split into four separate Work Packages (WPs) as detailed in the PEA and summarised in table 5-1. Further details on the individual WPs are provided within the following sections of this report.

Table 5-1: V2G Dynamic Headroom Control work packages

Ref	Description	Delivered by
WP1	Initial modelling using profile data	Loughborough University
WP2	Modelling with smart meter data	Loughborough University
WP3	Implementation feasibility	Loughborough University
WP4	Dissemination and closedown report	Loughborough University

5.1 Work package 1 - Initial modelling using profile data

Work package 1 included three main activities:

WP1 D1	Site selection for the project simulation analysis, as described in the Site Selection Report https://commercial.nationalgrid.co.uk/downloads-view-reciteme/709697
WP1 D2	A description of the proposed control algorithms, and the outline plan for simulation modelling in the Control Algorithms Definitions https://commercial.nationalgrid.co.uk/downloads-view-reciteme/709696
WP1 D3	Initial simulation results, using synthesized data, and modelling a future scenario where V2G would be deployed alongside the existing demand and together with a predicted growth in solar PV, heat pumps, and EV charging based on the Distribution Future Energy Scenarios 'Electric Engagement' option for 2035 https://commercial.nationalgrid.co.uk/downloads-view-reciteme/709695

The first activity in this work package was to select a set of substations for use in the simulation and modelling work. These substations were selected from across the four NGED license areas and included a variety of geographical characteristics (suburban, rural etc) and included both underground cables and overhead lines.

A risk assessment provided by the NG DSO LV Planning team was used to identify substations where an early uptake of V2G might be expected to exceed the available capacity. This assessment identified substations with a high number embedded generators, mostly solar PV, or a high installed capacity of these generators, relative to the rated transformer capacity. Substations

were also considered to be at risk where the LV feeders have long line lengths of either underground cables or overhead lines with a small cross-sectional area.

Since the project method relies on smart meter data to assess the available headroom for V2G, substations were also selected on the basis of having a sufficient uptake of smart meters.

The aggregated smart meter demand data for individual feeders was used in work package 2 as a baseline so that the available thermal capacity could be determined. This requires the demand data to be reasonably accurate, and therefore that the set of smart meters from which the data is aggregated should be those that are connected to the corresponding LV feeder. Experience from the SMITN NIA project has shown that errors in customer connection records can arise, and so a further selection method was employed, checking the proximity of the customer location to the assigned LV feeder. The selected set of substations therefore included an additional check that the set of customer connections included in the aggregated feeder demand would be plausible.

This process provided a set of 102 substations that could be used for the initial simulations in work package 1, and 86 substations that were suitable for the later modelling in work package 2. In practice, it was found that the network data for a few of these substations could not be imported into the modelling software and so these were subsequently dropped from the analysis.

Work package 1 also included an activity to define the control algorithms that would be investigated in the subsequent simulation work. These considered a volt-var control in which reactive power would be imported or exported to moderate the LV feeder voltages. This method operates at both high and low voltages, with reactive power being imported for voltages above an upper threshold, and exported for voltages below a lower threshold. The models also considered a volt-watt control method in which the active power exported by a V2G installation would be progressively ramped down for voltages increasing between a lower and upper threshold. For voltages above the upper threshold, the active power exports would be zero. A hybrid method using both volt-var and volt-watt control was also considered. The volt-var and volt-watt methods are illustrated in Figure 1 and Figure 2.

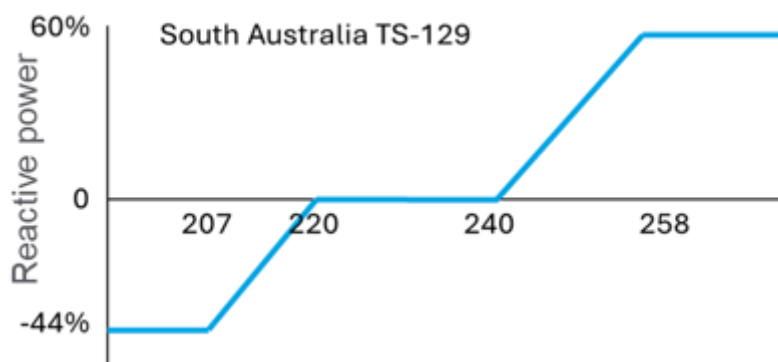


Figure 1 - Volt-var control

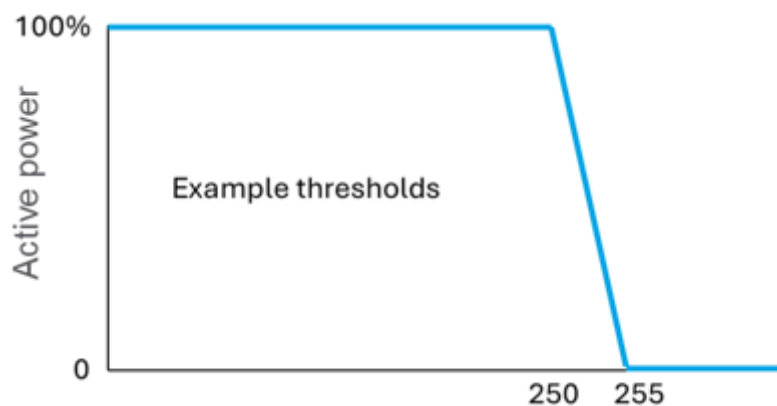


Figure 2 - Volt-watt control

A set of modelling scenarios was also identified. These were modified slightly as the simulation modelling developed, and included the scenarios listed below, either in the simulations with synthesized data in work package 1, or in the later simulations with smart meter data in work package 2.

Table 1 - Control scenarios for modelling

Scenario	Comments
Existing demand With no additional LCTs other than those already connected Without V2G	Assesses whether any voltage or thermal constraints have already been reached
Future LCT demand LCT growth added according to DFES predictions, taken to a future date where the first export constraint occurs Without V2G	Allow multiple possible future date scenarios to be reduced to a single year, derived individually for each feeder, where a constraint occurs. It is possible that no constraint will occur on some feeders for the foreseeable future.
As above, with V2G	Export constraints exceeded
Locally customised V2G export limit per customer	Customised per substation or feeder
Temporally customised V2G export limit	Limits set based on time of day
Volt-var control profile	Volt-var control profile, parameters customised per LV feeder
All devices following defined profile	Volt-var control profile, parameters customised per LV feeder and phase
Various frequencies of update are possible, e.g. seasonally, monthly, weekly	Volt-var control profile, parameters customised per LV feeder and for time of day
Volt-watt control profile	Volt-var control profile, parameters customised per LV feeder
All devices following defined profile	Volt-var control profile, parameters customised per LV feeder and phase
	Volt-var control profile, parameters customised per LV feeder and for time of day

The initial simulation modelling aimed to assess a future scenario where V2G uptake has become ubiquitous. This is supported by the NESO Future Energy Scenario for 2050 where a total installed capacity of 81 GW of V2G is predicted. For individual installations of 3.7 kW, this corresponds to around 76% of households, assuming current population levels. In practice it may be that a higher export power will be permitted for V2G, which would imply that they would occur at a lower proportion of households, although the expected export capacity across an LV feeder would remain the same, with a smaller number of higher power devices.

It was assumed throughout the modelling that a worst-case condition would be considered where all V2G installations on a feeder would export at the same time. In addition, it was assumed that all customers had their EV at home and connected, such that exports would be possible. This is representative of a response to a grid outage where V2G installations would be called upon to export, possibly incentivised by a relatively high reward payment to the customer. The timing of these export periods would be unpredictable and could occur at any time of the day. They could coincide the existing solar PV exports during the middle of the day, when demand is also low, but could also occur in the evening when other demands, for example due to heat pump operation, might be high.

The modelling considered the worst-case condition where the V2G exports coincided with high outputs from solar PV, and also lower domestic demand. The modelling included the operation of heat pumps, and also of EV charging (though not simultaneously with the V2G exports), with uptake rates of each of these technologies defined by the Distribution Future Energy Scenarios 'Electric Engagement' option for 2035.

Although the model only considered V2G exports in the middle of the day, the simulation method included a full one-year duration at half-hourly time resolution, and included the recharging of EV batteries following the export events. EV batteries were either recharged directly after the export period, or at a later point if the operation of the model already included EV charging at this time.

Details of the simulation software are included below:



Loughborough
University



CREST
Centre for Renewable Energy
Systems Technology

LV and HV Network Modelling

- Fully validated against measured end-point data in NGED NIA projects
- Integrated model of HV and LV as one
- Unbalanced analysis using 3×3 impedance matrices
- Network data imports from GIS and asset data
- Synthesises service connections and implements SMITN phase identification
- Proven for modelling license-area scale
- Demand data from smart meters, LV monitoring, synthesis from profiles, CREST Demand Model
- Statistical and empirical models for solar, EVs and heat pumps
- **Fully customisable Python for bespoke studies**



Validated power-flow analysis

LV and HV network modelling software was originally developed to support WPD Losses Investigation NIA project. Detailed network models were validated against fully instrumented HV and LV feeders. Models were created with power-flow analysis for HV and LV feeders throughout all four license areas.

Demand data

Models use smart meter data where available, supplemented by scaled profiles to represent non-SMETS customers. LCT modelling is configurable and can use data from research datasets and statistical models derived from empirical results, e.g. EV profiles from NGED Electric Nation. Demand data can be calibrated against TSDS and LV monitoring data.

Combining smart meter data with LCTs

Models developed for the NGED V2G Dynamic Headroom Control NIA project use smart meter voltages as a baseline, combined with synthesized demands to explore the available headroom for LCTs.

Dr Andrew Urquhart and Dr Murray Thomson

a.j.urquhart@lboro.ac.uk

Figure 3 – Modelling software

The simulation results included the following metrics for each LV feeder:

Table 2 – Simulation metrics

Maximum customer voltage	Calculated for each LV feeder at 1-minute resolution at each single-phase customer connection, taking maximum over time and over three phases.
Minimum customer voltage	Calculated for each LV feeder at 1-minute resolution at each single-phase customer connection, taking minimum over time and over three phases.
Mean cable losses	Averaged for each LV feeder over the one-year simulation period at 1-minute resolution.
Maximum RMS first branch current	Maximum for each LV feeder over the three-phases of the RMS current in the first cable branch from the substation on each feeder, averaged over the one-year simulation period at 1-minute resolution. The first branch typically provides the most significant current constraint as it carries the aggregated demand for all customers on the feeder.
Current overloads	Numbers of mains branches for each feeder using the peak current from a half-hourly daily profile, calculated according to the Elexon seasons, for each cable branch and over the three phases.

5.2 Work package 2 - Modelling with smart meter data

Work package 2 included three main activities:

WP2 D1	Phase identification of single-phase smart meter connections. Available upon request.
WP2 D2	Simulations with smart meter data, with the method described in detail and simulation results. This deliverable used an initial sample of smart meter data so to give earlier visibility of the results, with simulations being repeated in WP2 D3. https://commercial.nationalgrid.co.uk/downloads-view-reciteme/709695
WP2 D3	A further set of simulation results, extending the results from WP2 D2, with the smart meter data collected over a longer period so that higher exports from the existing solar PV during the summer period would be included. In addition to extending the measurement dataset, the report for WP2 D3 included improved metrics to improve the interpretation and presentation of the results https://commercial.nationalgrid.co.uk/downloads-view-reciteme/718289

In conventional power-flow analysis, such as would be used in LV planning tools, the simulation has knowledge of the demand for each individual customer. This is not straightforward when using smart meter data to define the existing demand which is only available when aggregated across a group of customers so that individual customer privacy can be retained. Typically, NGED aggregate the demand across all customers on an LV feeder.

To resolve this difficulty, a new super-position simulation method has been developed for this project in which the simulated impact of V2G operation, in terms of customer voltages and feeder currents, is combined with measured voltage data from smart meters to represent the existing demand. The individual customer demands are not known, but so the simulation instead uses their impact, in terms of the measured voltage.

This method has two potential applications in relation to the projects. In this NIA project, the approach has been used to assess whether V2G exports will exceed the headroom available, when considered in combination with the existing demand. In this context, no additional demand or generation from other future low carbon technologies (LCTs) has been included – just the existing demand and the V2G exports.

The super-position method could also be used at some time in the future, potentially as part of a Business as Usual approach to assess the impacts of further uptake of low carbon technologies. By the time that V2G has become commonplace, it is expected that the uptake of other low carbon technologies would also have increased. The impact of V2G could still be assessed using the same super-position method as has been trialled here, but the existing demand would include more low carbon technologies than at present.

The combination of measured voltages from smart meters with a voltage from simulation relies on several assumptions and requirements. Firstly, there is an underlying assumption that the voltage phase angles are equal, such that it is possible to combine a measured voltage amplitude with a differential voltage drop from the simulations. This is a reasonable approximation as voltage drops along LV feeders are small relative to the nominal 230 V supply, and so cause negligible deviation to the nominal voltage phase angles at 120° intervals.

Secondly, when the voltage drops due to V2G are calculated using a constant power model for the loads, the simulation should operate at a nominal voltage that is similar to the measured voltage range. In a constant power load model, the export power for V2G would be specified as 3.7 kW, for example, and then the power-flow analysis determines the load current required to accept this power, based on a calculated voltage that allow the substation busbar voltage and the voltage drops along the feeder. The models used here assume a nominal 245 V at the substation busbar, and then calculate the voltage drops along the feeders.

To combine the simulated voltages with the measured voltages, the simulated voltage differences for each customer, relative to the nominal 245 V at the substation, are added to the measured voltages from the smart meters to estimate the total voltage that would be found if the existing demand and the V2G exports were combined.

This addition process requires knowledge of the phase connections for each single-phase customer. These were determined by applying the phase identification methods developed in the SMITN NIA project, using a clustering approach, and with several further enhancements to improve the consistency of the results.

Although the site selection for this project aimed to find substations with a high uptake of smart meters, on average around 80% of customers, many of the LV feeders include customers without smart meters and for whom only the estimated annual consumption (EAC) is known. A half-hourly time-series demand profile is constructed for these customers using the appropriate Profile Class in the Elexon Profiles, and then their total half-hourly demand is shared equally between each of the phases available on the LV feeder.

Similarly, although the total demand from smart meter customers is known, this is not yet available for individual phases on the LV feeder. The aggregated smart meter demand is therefore shared between the available LV phases by proportion of the number of smart meters identified on each phase.

The super-position method can also estimate the combined current in the feeder cable branches connected to the distribution substations. The existing complex power demand in these branches is known from the aggregated smart meter demand data, and the current can therefore be approximated using a nominal voltage, for example based on the measurements from a smart meter located near to the substation. The demand from the V2G can be added to the measured demand so that the combined current can be calculated and compared against the rated cable

capacity. The ratio of the estimated current to the rated current is defined here as the utilisation factor, and the thermal headroom is calculated assuming that operation up to the full rated capacity is possible. In practice, some margin might be required, in which case the methodology would remain the same but there would be a reduced thermal headroom available.

One constraint of this method is that the impacts of V2G cannot be combined with the existing demand at customer connections without a smart meter. Since the 76% predicted proportion of future customers with V2G, is similar to the 80% uptake of smart meters in the selected sites, the modelling assumes that all of the V2G installations are located together with the existing smart meters. This is considered a reasonable approximation as customers with a smart meter are more likely than those without a smart meter to have an EV, as demonstrated in the SMITN NIA project.

5.3 Work package 3 - Implementation feasibility

Work package 2 included two main activities:

WP3 D1	Definition of a set of implementation risks and issues that would be addressed by further modelling
	Available upon request

WP3 D2	Implementation risk simulation results
	https://commercial.nationalgrid.co.uk/downloads-view-reciteme/718290

Work packages 1 and 2 of this project demonstrate the benefits of controlling exports to the grid from electric vehicle (EV) charge points with V2G capability. There are potential implementation risks associated with the algorithms proposed for V2G control and these may be explored in a future trial of V2G control methods. Ahead of any trials, and in preparation, further targeted simulations were developed to explore some of these risks in more detail. The results of these simulations would inform the design of a hardware trial and would help to avoid any obviously foreseeable problems.

The first deliverable for WP3 defined a set of risks that could be explored. Results addressed most of these issues although the issues of response to grid disturbance and change due to maintenance were not included as the required response was by then already developed in the use of targeted volt-watt control thresholds for individual substations and feeders.

The implementation risks considered were:

Control instability

There is a possible scenario that one V2G charger will take action to mitigate voltage rise, either importing reactive power or reducing exports, thereby reducing voltage for other V2G chargers on the same LV feeder, such that these other V2G chargers then see a lower voltage and increase exports.

This could lead to the first V2G charger then taking further action to mitigate voltage rise and further increases in exports from the other V2G chargers. This mechanism could introduce a high level of unbalance between the V2G chargers with one or more having exports severely impacted and other having no impact.

Conversely, multiple V2G chargers may respond together to a high voltage and then take action to reduce voltage rise. Subsequently, when the voltage is reduced, it is possible to either reduce

imports of reactive power or increase exports. This then raises the voltage again, returning to the initial condition. This mechanism could lead to the V2G chargers constantly switching exports on and off, causing a voltage flicker problem, and also failing to limit the peak voltage rise, even though average voltages would be reduced.

Partial compliance with standards

There is a risk that not all V2G chargers will follow the desired standards. This reduces the effectiveness of the control action taken by those that implement the standard, increasing the constraint to their active power exports.

During the development of the simulation work work package 2 it was realised that the existing smart meter data already includes voltage rise due to solar PV. Rather than including additional devices to the model that do not comply with standards, the simulations instead needed to consider synthetic baseline data where no existing voltage rise occurred. The modelling then also added in a degree of non-compliance to confirm that the same effects were observed as with the existing smart meter data where voltage rise due to solar PV is already present.

Distribution transformer tap settings

The smart meter voltage data now available for the selected feeders enables analysis of the benefits of selecting different tap settings at the distribution transformer.

Where voltages on LV feeders are with V2G operating in the absence of controls, the analysis demonstrated whether the voltage ranges could be compliant if the tap setting was changed.

For this analysis, it was deemed that the V2G voltage range could be accommodated by a fixed tap setting change if the maximum range between upper voltages while exporting and lower voltages while importing, calculated over all time samples, is less than the regulatory voltage rise.

This approach is clearly an approximation as it implies that tap settings are continuous, rather than discrete, and also omits allowing any margin for voltage drops along the HV feeder.

A similar approach was adopted for on-load tap changes, where the maximum voltage range between exports and imports could be considered individually for each half-hour period, rather than allowing for the difference between the maximum voltage and the minimum voltage.

It was initially thought that this work would also investigate stability interactions between the individual V2G controls and the operation of the on-load tap changer but this was not possible with the information available on real-time operation of the control systems.

Communications system

The proposed algorithms also imply a more complex information sharing and feedback process than is currently employed in the control of consumer appliances. These relationships also have risks associated with them, and a trial may be an appropriate means of investigating their feasibility. The WP3 D1 document sets out the relationships as they are currently envisaged, as a guide to the participants and activities needed for a trial.

5.4 Work package 4 - Dissemination and closedown report

Work package 4 included two main activities:

WP4 D1	Preparation of the dissemination material and participation in webinar presentations, and wider disseminations, as required. https://www.youtube.com/watch?v=q3u7r20Kbv8&t=2s
WP4 D2	Preparation of the closedown report (this document) as per NGED and ENA requirements. This report.

6. Performance Compared to Original Aims, Objectives and Success Criteria

Full details on the performance against original objectives, and success criteria are provided in the tables below.

Table 6-1: Performance compared to project objectives

Objective	Status	Performance
Objective 1. Evaluate V2G control techniques to understand their effectiveness in maintaining LV assets within operational ranges in a desk-top environment	Complete	Simulation results have demonstrated that volt-watt control can maintain LV assets within voltage and thermal limits. Volt-var control can mitigate voltage rise but has an associated risk that thermal overloads may increase.
Objective 2. Assess the benefits of new techniques where smart meter data is used to customise V2G control methods, varying either with location, time of day, or as the uptake of LCT appliances progresses	Complete	Control thresholds have been modelled with settings customised for individual substations, or individual LV feeders, demonstrating the increase in mean exported power that is enabled by a more granular resolution. A similar benefit is available where settings are customised based on the time of day. The reports describe a communication method by which the control thresholds could be updated accordingly as the uptake of V2G progresses. The results apply equally to exporting appliance that conforms to the volt-watt control standard.
Objective 3. Quantify the impacts on losses of reactive power control techniques	Complete	The simulation modelling included calculation of losses in the first branch on each feeder from the selected substation. These results showed the increase in losses due to V2G, and also the impact on losses of the V2G control methods. In all cases, V2G increases losses, as would be expected as the LV feeder utilisation increase to support the exports and subsequent imports. Volt-var control was found to increase losses over and above the increase due to V2G alone, due to the additional current amplitude associated with reactive power flows.
Objective 4. Assess the impact on customers, in terms of the likelihood and equity of power constraints	Complete	Although volt-watt control can maintain LV assets within voltage and thermal limits, this is achieved by reducing the exported active power. This would represent a loss of revenue to customers who are participating in virtual power plant schemes whereby aggregator pay for exports to supply grid support services. Customers located at the ends of LV feeders are likely to be constrained more, and those

Objective	Status	Performance
		nearest to the substation would be constrained less. An alternative control scheme was demonstrated in which all the customers on a feeder were equally constrained, thereby achieving a fairer distribution of export powers within the LV feeder. However, this reduces the overall level of exports. Differences in constraints between substations or feeders would still remain.

Table 6-2: Status of project success criteria

Success Criteria	Achieved	Performance
Criteria 1. A clear understanding of the expected benefits of different V2G control strategies that are the focus of this study, and in particular of the additional value obtained if control parameters are updated locally and dynamically rather than being pre-set equally on all devices. This would lead to the specification of control algorithms that can be assessed in a future trial using real V2G devices on live LV feeders.	Achieved	The voltage-based control strategies have been shown to have clear benefits from the perspective of the network operator, maintaining LV assets within voltage and thermal limits. In the absence of controls, V2G could cause a high probability of over-voltage or thermal overload. LV feeders could be reinforced to overcome this risk, but instances where the worst-case exports occur may be rare. The results demonstrate the benefit of voltage-based control, that could be mandated by standards, as a backstop to maintain assets within capacity limits.
Criteria 2. A clear understanding of the optimum level of control interaction, where improvements in power exports and customer experience fairness are balanced against increased communication overhead.	Achieved	The simulations have indicated that real-time control of active or reactive can be managed autonomously within individual V2G installations, but that there is a benefit to periodic updates to the control parameters that are used. The proposed updates appear feasible, although an integrated system involving communication between the DNO, suppliers or aggregators, and the V2G devices is required. Methods to increase customer fairness have been demonstrated but this requires a much higher communications overhead, and has the further disadvantage that achieving fairness of mean exports within an LV feeder results in lower overall export power. The increased communications overhead would also not address the issue of unfairness between LV feeders where the uptake of V2G relative to the feeder hosting capacity may be very different.

7. Required Modifications to the Planned Approach during the Course of the Project

Development of the simulation tools proved to be more time consuming than expected due to the complexity of the iteration processes that were required. This caused completion of the simulation deliverables to be delayed relative to their planned timescales. Conventional power-flow analysis method already involves an iterative approach, with voltages and currents adjusted such so that Kirchoffs voltage and current laws are satisfied and to meet the boundary conditions relating to the required power delivered to or from each connected to the network. For the purposes of this project, the power exported from each V2G installation could potentially vary in response to the voltage, and variations of export power from any one V2G installation would therefore change the voltages seen by every other V2G installation. Development of a method to handle these multiple interactions took some time, but a method was identified and successfully delivered.

Despite delays specified above, the project was delivered on time and budget.

8. Project Costs

Project spend and comparison with the initially budgeted figures are provided in the table below.

Table 8-1: Overall Project Spend

Activity	Budget	Actual	Variance (%)
NGED Project and Programme Management	£57,646	£55,814	-3%
NGED Smart Metering Support	£21,033	0	-100%
Loughborough University Services	£302,403	£302,403	0
Contingency	£38,108	£0	-100%
Totals	£419,190	£358,217	-14.5%

- NGED project team was efficient in providing smart meter data for the simulation studies as part of the wider company activities around smart meter data; therefore savings was made on the project under 'NGED Smart Metering Support' category;
- The project was delivered to the original budget. Release of the contingency funds was not required.

9. Lessons Learnt for Future Projects and outcomes

Table below summarises key lessons learnt on the project.

Table 9-1: Lessons learnt

Ref	Area	Description
Objective 1	Evaluating V2G control techniques	<p>In models of V2G in context of a DFES 2035 scenario together with growth in solar PV, heat pumps, and EV charging, the additional of V2G from all installations, and without controls, increases the number of feeders with over-voltage from around 2% (without V2G) to around 25% (with V2G) [WP1 D3].</p> <p>The risk of thermal overloads also increases with V2G in this model, with 32% of feeders having one or more overloaded cables [WP1 D3].</p> <p>Coordinated recharging after an export event contributes to this risk of current overloads. Applying a short-term temporal diversity to the recharging reduces the proportion of feeders with an overloaded cable to around 20%, where V2G is included in the absence of control methods [WP1 D3].</p> <p>Adding voltage-based control, in this model where there is a high uptake of solar PV generation that does not follow the control standards, reduces the number of feeders with over-voltage to around 20%, and also reduces the extreme maximum voltages observed [WP1 D3].</p> <p>Volt-watt control effectively mitigates the increase in thermal overloads in this model, so that there is no notable increase relative to the likelihood without V2G. Volt-var control provides no reduction in the risk of thermal overloads [WP1 D3].</p> <p>Where V2G installations are unbalanced between phases, exports on the highly loaded phase may be highly constrained by volt-watt control. During a subsequent recharging period, coordinated imports on the less loaded phases may increase the neutral conductor potential and so cause voltage rise on the phase that had been constrained for exporting. Since the volt-watt control (as defined here) only acts on exports, and since the import power is maintained at an assumed 7 kW, even if the duration of recharging is reduced, this effect can cause high short-term voltage rise that is greater than the voltage rise during exporting [WP1 D3].</p> <p>In a second model where V2G operation is combined with the existing smart meter data, customers have a 43% probability of having over-voltage if V2G has no controls, and if all V2G customers export simultaneously. There is a 13% probability that feeders will have thermal overloads [WP2 D3].</p> <p>These impacts can be mitigated by volt-watt control, with results depending on the threshold settings used. If thresholds are set around the regulatory upper voltage limit of 253 V, the probability of over-voltage is reduced to only 1%, and the probability of thermal overload reduces to 1.5% [WP2 D3].</p>

Volt-var control only halves the probability of over-voltage to 25%, but also increases the probability of thermal overload reduces to 26%. Volt-var control therefore appears less applicable for use when over-voltage are very high, and caution would be needed to ensure that the additional reactive power does not cause thermal overloads. However, in a more typical scenario, either when V2G uptake is less, or when few customers are simultaneously exporting, volt-var control may allow for voltage control without the loss of active export power, and while remaining within the available thermal headroom [WP2 D3].

A combination method of volt-watt-var control has similar effect to volt-watt control in ensuring that over-voltage is avoided, but also increases the probability of thermal overloads, to 17% of feeders, though still less than with volt-var control alone [WP2 D3].

These results demonstrate that setting volt-watt control thresholds at the same level as the regulatory upper voltage limit does not guarantee compliance with either voltage or thermal limits of the LV feeders. There is a remaining risk of thermal overloads, since the voltage-sensing control methods do not detect this, and also a residual risk of over-voltages. These over-voltage arise because the smart meter data already includes some instances where voltage rise occurs, due to exports from existing solar PV generation that do not follow the volt-watt control. If V2G customers connected near to the substation experience a voltage below the volt-watt control thresholds, then active exports will continue, and these exports will cause voltage rise for solar PV generators further along the feeder, in some cases above the regulatory limit [WP2 D3].

These risks can be resolved by setting a volt-watt control threshold that is lower than the upper regulatory limit, and a threshold around 245 V was found to be effective in reducing the probability of over-voltage and thermal overload so that it was no greater than in the existing smart meter data. However, setting this limit as a default for all substations and for all time would significantly constrain the export power from V2G, not only in the extreme cases where all customers are exporting, but also in the more typical scenario where V2G uptake is lower or where only some customers are actively exporting. A more dynamic approach is therefore beneficial [WP2 D3].

Objective 2	Customising V2G control with smart meter data	A new super-position method has been developed so that power-flow analysis can be implemented in a hybrid model where simulated additional demands, in this case from V2G, are combined with the impact of the existing demand measured by smart meters. This allows the power-flow analysis to proceed without the requirement to know the individual customer demands, overcoming the difficulty that this demand data must be aggregated to maintain privacy [WP2 D2].
----------------	---	---

Setting a default low volt-watt control threshold for all customers, and for all time periods, causes a significant loss in the export power capability. Thresholds could be customised for each distribution substation, or for each LV feeder, and set as high as possible while avoiding over-voltages or thermal overloads, then the export capacity can be increased. Simulations models with volt-watt control, with a default 245 V volt-watt upper threshold, showed an increase in mean exported power from 0.5 kW where all customers have a default threshold, to 1.0 kW if thresholds

are customised for each substation, and 1.5 kW if thresholds are customised for each LV feeder [WP2 D3].

If the default threshold is set higher, there is less incremental benefit from customising the thresholds for substations or feeders, and the risk over over-voltages or thermal overloads is greater. However, the mean export powers are also higher [WP2 D3].

Models where thresholds were customised on a seasonal basis did not show significant increase in mean export power. If all V2G customers export simultaneously, the combined power is higher than the existing demand, such that optimising around seasonal or diurnal variations is not effective [WP2 D3].

Thresholds could be selectively enabled on individual feeders at pre-determined half-hours of the day, with half-hours requiring no control identified from prior experience using smart meter data. This provided an increase in the mean export power per customer to 0.7 kW, compared to 0.5 kW if the thresholds were applied throughout the day. A lower increase to around 0.55 kW is possible if the threshold is enabled for any feeder at the substation that would exceed capacity limits. These results differ from the figures noted above where thresholds are optimised spatially, since here the lower threshold is either enabled or not, whereas in the model where thresholds were optimised per feeder, the algorithm applied higher thresholds where these would still allow compliance with voltage and thermal limits [WP2 D3].

An idealised model was considered where the volt-watt threshold were enabled for individual half-hours, rather than in specific half-hours of the day. A practical implementation would require perfect foresight of the demand, or a real-time communication system. This indicates an upper bound to the export power that could be achieved by selectively enabling the thresholds. Compared to 0.5 kW mean export power with a 245 V threshold applied uniformly, the selecting approach provides mean export power of 1.2 kW per customer [WP2 D3].

Overall, the modelling with temporally enabled thresholds provides a lower improvement in mean export power, than a spatial approach where the thresholds are set to the highest level possible per feeder [W2 D3].

Objective 3	Quantifying the impact on losses	<p>In models of V2G in context of a DFES 2035 scenario together with growth in solar PV, heat pumps, and EV charging, the additional of V2G exports from all installations for 30 minutes each day, and without controls, increases worst-case feeder losses to a mean power of 2500 W, compared to around 250 W without V2G [WP1 D3].</p> <p>Adding volt-watt control in this model reduces the losses with V2G so that they similar to losses without V2G. However, volt-var control increases losses further, with the worst-case feeder having mean loss power of 3500 W. [WP1 D3].</p> <p>In models where V2G was added to the existing demand based on smart meter data, losses could be calculated for the feeder cable branches that connect to the substation busbars. The total existing demand in these branches is recorded in the aggregated demand for each feeder, though</p>
-------------	----------------------------------	--

an approximation is still required to apportion this between phases. Loss calculations for these feeder branches were consistent with the simulations based on synthetic demand data. Losses were approximately quadrupled where V2G was added to the existing demand, and doubled again if volt-var control was applied to mitigate voltage rise. The additional losses here were due to the increase in current amplitude associated with the reactive power. With volt-watt control, losses were only doubled relative to the existing demand [WP2 D3].

An increase in losses is to be expected with V2G, even when controls are applied, as the export powers increase the utilisation of the feeder cables, up to a limit imposed by voltage and thermal limits. More generally, losses associated with V2G might also consider the impact of the round-trip battery charging efficiency, in addition to the feeder cable losses. These losses may be considered acceptable relative to the value of the energy storage service provided to the grid by V2G. Although losses have been considered here for a worst-case (in terms of network impact) scenario where all customers export at the same time, this may be a rare occurrence, and in a more typical scenario exports from one customer may serve imports for their neighbours [WP2 D3].

Objective 4	Assessing the impact of constraints	Simulations with smart meter data demonstrated that the mean output power per customer would be significantly reduced if volt-watt control was employed to ensure network compliance, from an assumed permitted export power of 3.7 kW, down to 0.5 kW if a 245 V threshold was used, or 2.6 kW with a threshold around the regulatory limit voltage. This represents a loss of income to constrained customers [WP2 D3].
----------------	---	---

On feeders where the thermal capacity is not a constraint, and in the absence of other generators at the feeder ends that would also cause voltage rise without implanting volt-watt control, the thresholds could be set at the regulatory limit. Constraints would only then occur when necessary to ensure voltage compliance. The power constraints listed above would then only apply on rarer occasions when all V2G customers were exporting simultaneously. However, if the thresholds are set lower than the regulatory limit, for example as a default setting used for all customers, to allow for the possibility of thermal constraints or voltage rise from other uncontrolled devices, then the loss of export would be greater [WP3 D2].

Export power constraints have been shown to have a greater impact on customers at the ends of feeders, and a lesser impact on customers nearer to the substations. Relative to the mean export power, the advantage to those nearest the substation is greater than the disadvantage to those at the feeder ends. [WP2 D3].

An alternative control algorithm has been demonstrated where the volt-watt control responds to the maximum voltage seen by any V2G customer on a feeder, rather than the voltage at the individual points of connection. Since this same maximum voltage is used as a control signal by all V2G installations, the mean export power from all customers on the feeder is the same. This demonstrates that the inequity in export power can be resolved [WP3 D2].

This method to impose a more equal distribution of export constraints within a feeder has the disadvantage that the overall mean export is reduced, from 2.6 kW (assuming volt-watt thresholds at the regulatory limit) to 2.2 kW. By adopting an algorithm in which a greater proportion of the export power is supplied into the LV feeder at points further from the substation, voltage rise on the feeder is increased, and so exports become further constrained [WP3 D2].

A practical implication of this approach to fairness is that communications between all the V2G installations would be needed, to share their voltage readings so that the maximum could be identified and so that this information could be distributed [WP3 D2].

Given that it is not possible to ensure fairness in constraints between LV feeders where the uptake of V2G and the feeder hosting capacity may be different, the value of ensuring fairness within an LV feeder might be questioned, especially where this causes the export power on average to be reduced [WP3 D2].

Success
Criteria 1 Understanding
the benefits of
V2G control

Modelling has demonstrated that simultaneous exports from V2G, where the uptake is in line with NESO predictions, will cause many feeders to exceed upper voltage limits and to exceed their thermal capacity. DNOs could reinforce to allow for this eventuality, but instances where this export scenario occurs may be rare.

Limiting the numbers of V2G installations by rejecting connections via the LV planning process would significantly reduce the benefit from V2G to wider grid balancing, and a mean output per customer of only 0.7 kW would be possible for the selected project feeders [WP2 D3].

An alternative approach is to implement a voltage-based control, which would likely require devices to comply with additional mandatory standards. Volt-var control may be used on feeders where the associated increase in thermal loading is still within the cable capacities. Where voltage limits may be exceeded, or where thermal ratings are a constraint, volt-watt control would be deployed to ensure feeders remain within capacity limits. This implies periodic updates to the control strategy such that the appropriate control method could be selected.

Where V2G uptake is high, as in the modelling for this project, an initial option could be to deploy volt-watt control with thresholds set at the upper regulatory voltage limit. Setting lower thresholds would constrain export powers, and may not be required. However, a lower threshold would likely be required for feeders where thermal capacity is the constraint, or where additional voltage rise from uncontrolled devices requires exports from V2G to be further reduced.

A targeted approach, therefore allows for volt-watt control to be effective where necessary in order to ensure compliance with voltage and thermal limits, but to avoid constraints on other feeders where this is not required.

The use of lower thresholds could be applied for all customers on a selected substation, but applying the thresholds for individual feeders provides an improved overall mean export power.

Modelling of implementation effects has demonstrated the possibility for instability when multiple V2G devices make conflicting volt-watt control adjustments to their export power. When one device sees a high voltage and reduces exports, this may allow another device to increase exports. For most of the simulation work in this project, the modelling software was designed to avoid these effects and to demonstrate a stable state that could be achieved. However, simulation models in which the iteration process was allowed to progress so that each V2G took repeated control showed that instability could occur. A smoothing method to address this was also demonstrated. As with many control systems, the feedback mechanisms were shown to allow a steady-state offset to remain, such that the maximum voltage on the LV feeder would, on average, be higher than the level set by the volt-watt control thresholds.

These stability effects are highly dependent on the frequency with which the V2G control updates are applied, the averaging periods used for voltage measurements, and on any hysteresis applied to the control feedback process. There is scope for further simulation work to investigate this aspect of volt-watt control, but a hardware trial would also be highly valuable to demonstrate that stable operation can be achieved.

Success Criteria 2	Understanding the optimum level of control	<p>The modelling has assumed that the real-time operation of the V2G installations remains autonomous and that the communication for control purposes would consist of periodic updates to the control parameters. The frequency of these updates has not been determined in this project, and would depend on the rate of V2G uptake, and on the impact of tariffs or control signals from aggregators that would cause exports from V2G to occur simultaneously. A working assumption would be that update are required no more frequently than on a monthly basis.</p> <p>The modelling work has considered several approaches where a higher rate of communications would be required, for example to share voltage readings between the V2G installations on an LV feeder, with the aim of improving the fairness of export constraints. Since this does not resolve the inequality of constraints between feeders, the benefits of improving fairness within a feeder do not seem compelling, especially if this can avoid the need for real-time communications between V2G installations.</p> <p>The modelling has also considered the use of individual threshold settings for each V2G installation, with the aim of reducing overall export constraints and improving fairness. Results from this modelling did not show a clear benefit relative to the use of a common volt-watt control threshold for all V2G customers on a feeder [WP2 D2].</p> <p>The simulation results have also been analysed to determine whether the voltage ranges could be resolved by the use of either a fixed transformer tap change, or by the installation of an on-load tap changer at the distribution transformer. This analysis assumed that the proposed amendment to the regulated voltage range, allowing 230 V \pm10%, would be implemented. With these wider voltage ranges, around 30% of the LV feeders modelled would have no constraint due to V2G, and 70% would require some form of intervention. The voltage constraints on approximately 21% of feeders could then be resolved with a fixed tap change (under idealised assumptions), and a further 9% with an on-load tap changer. The remaining 40% of feeders would require a further</p>
--------------------	--	--

method to ensure voltage compliance, for example the volt-watt V2G control.

A possible scenario may see volt-watt control thresholds initially set high, when number of V2G installations are low, but then reduced for specific feeders as the number of installations increases in order, for example, to address over-voltage due to existing voltage rise. These lower thresholds would then constrain exports even at times when fewer V2G installations are exporting, and these constraints may be considered unacceptable to customers. A fixed tap change may then be made which may either resolve the problem or reduce the frequency with which over-voltages would occur. This could then allow the volt-watt control thresholds to be raised.

Each of these changes to the control thresholds would require the DNO to identify the need for an update, based on monitoring voltage and aggregated demand data from smart meters. Ideally, the SMITN phase identification methods would be applied such that demand aggregation groups could be defined for individual phases and feeders. The DNO would then pass instructions to the service aggregator that manages the V2G exports on behalf of the customer. Typically this may be their energy supplier, who would set tariffs or send control signals to the V2G to determine when the exports are required. The DNO would need to hold records identifying the appropriate supplier or aggregator for each V2G installation, and the supplier or aggregator would transfer the updated control thresholds to the V2G device.

Although most of the components of this process are already in place, the operation of this communication path appears not to be well proven. This would be a key feature of a future V2G trial.

10. The Outcomes of the Project

The project outcomes include the following conclusions:

- As V2G uptake develops, simultaneous exports are likely to cause voltage limits to be exceeded for many customers, and thermal limits to be exceeded for many feeder.
- Concerns relating to voltage rise and thermal overloads due to exported power would apply equally to other exporting low carbon technologies, for example domestic battery energy storage systems, and also to solar PV. For convenience we refer simply to the example of V2G in our discussion.
- Additional control standards should be considered to ensure that V2G can be adopted by a large proportion of customers, providing an energy storage service to the grid, while also maintaining compliance with voltage and thermal limits.
- The operation of volt-var control, volt-watt control, and a combination volt-watt-var control, have been investigated using a set of 86 NGED substations where V2G might be expected to cause an early risk. The modelling shows that volt-watt control is effective in ensuring that V2G exports do not exceed feeder capacity limits.
- Volt-watt control appears most applicable to ensure compliance with voltage and thermal limits but volt-var control may be useful where V2G uptake is lower and where the increased current amplitude associated with reactive power flows does not exceed thermal limits.
- Volt-watt control provides a backstop but causes customers to lose revenue, so could be seen as a backstop while other interventions are deployed.
- Losses are increased with V2G, in the absence of controls, and to a lesser extent when V2G operates with volt-watt control. Volt-var control increases losses further, due to the additional current amplitude for reactive power flows.
- The simulation results have confirmed that the export power constraints with volt-watt control are unfair between customers on the same LV feeder. Those nearest to the substation are constrained less, and those at the feeder ends are constrained more.
- Resolving this inequity is possible, though may need communications between V2G installations, but would lead to a lower mean export power overall. Addressing concerns of inequity within LV feeders would not resolve the inequity between customers on different feeders or substations.
- If volt-watt control thresholds for V2G are set around the regulatory upper voltage limit, it is still possible for over-voltages to occur if other appliances that do not implement the volt-watt control are present on the feeder. Control of voltages within the regulatory limits also does not guarantee compliance with thermal limits. There is therefore a need to set lower thresholds on some LV feeders.
- If a single threshold setting is uniformly deployed, for example as a factory default, this would need to be set lower than the regulatory limits to ensure compliance. This would result in many customers having constraints applied on feeders where it is not required, or at times when not all customers are exporting. This could represent a significant reduction in the value of V2G in providing an export power service to the grid.

- Dynamic control thresholds to be set lower on substations or LV feeders where necessary. The lower thresholds would only be invoked when smart meter data indicates a risk of over-voltages or thermal overloads. Although this referred to as 'dynamic' control, the real-time operation of the V2G power electronics would continue to be autonomous, but with periodic update to the control thresholds.
- Results indicate that a spatial deployment of lower thresholds, to targeted substations of LV feeders, is more successful than a temporal deployment, for example by enabling the thresholds only at some times of day.
- Temporal deployment will require a communication path between the DNO and each V2G installation for periodic updates, possibly via the supplier or aggregator. A process has been developed as a possible means of implementation.
- Changes to fixed tap settings at the distribution transformer, or the installation of an on-load tap changer at the distribution transformer, could also maintain voltages within limits in some cases. These approaches might be adopted if V2G exports are frequently being constrained by volt-watt control, for example where the control thresholds have been set below the regulatory voltage limit.
- Even where fixed tap changes or on-load tap changers do not fully ensure compliance with voltage limits, these approaches may reduce the probability of constraints being applied. Voltage-based V2G control techniques provide a backstop until other tap change interventions can be deployed. Dynamic variation of volt-watt control allows for thresholds to be adjusted once other interventions have taken place.
- The real-time operation of voltage-based V2G control has the potential for instability, as control actions taken at one V2G installation affects voltages seen by neighbouring installations. Results have demonstrated this effect, and that averaging methods can mitigate the voltage variations that could be caused. A steady-state offset between the mean voltage levels and the control threshold settings is expected.
- The impact of recharging after an export event also needs to be taken into account, especially if this is also coordinated such that there is low diversity between customer demands. Recharging has been assumed to use the rated import power, for example 7 kW, rather than the lesser 3.7 kW assumed here as the permitted export power. The voltage drop during coordinated recharging, and thermal overloads, may be a greater concern than operation during exports. Volt-var and volt-watt control, as modelled in this project, do not mitigate this so additional standards may be required to mandate temporal diversity for recharging.

11. Data Access Details

V2G Dynamic Headroom Control project reports are available on the NGED Innovation webpage under 'Documents and Links' section:

<https://commercial.nationalgrid.co.uk/innovation/projects/v2g-dynamic-headroom-control>

If you've got a specific request regarding this project please get in touch via a dedicated email address: nged.innovation@nationalgrid.co.uk

12. Foreground IPR

The following foreground IP rights have been generated as part of this project (owned by Loughborough University):

- Methods to define voltage and thermal capacity headroom based on smart meter data.
- V2G modelling simulation tools comprising a power-flow analysis with added customisation to model LCT demand and the operation of V2G voltage-based controls.
- Novel demand modelling approach using smart meter voltage data to characterise impact of existing demands and superposition of voltage drops due to anticipated future demands.
- V2G control method for improved fairness of constraints within an LV feeder.
- Improved two-stage phase identification for single-phase customers using three-phase meters as cluster reference, single-phase clustering within feeders, and association of phase clusters between feeders.

13. Planned Implementation

The findings of this project provide a solid understanding of the potential benefits and limitations of voltage control techniques on LV network with a specific example explored around V2G application. The results are based on a simulation model and therefore a logical next step would be to test it in the controlled environment via a trial where the operation of the control techniques in question could be designed and tested under close supervision to understand real-time operation and effectiveness.

At the moment of writing this report, the possibility of the trial is being assessed to confirm:

- What low carbon technologies should be priorities and included in the trial.
- What are the wider industry initiatives around voltage control and V2G that need to be considered before/or as part of the trial.
- Prioritisation of V2G control as part of RIIO-ED3 planning.

14. Contact

Further details on this project can be made available from the following points of contact:

nged.innovation@nationalgrid.co.uk

Innovation Team

National Grid
Pegasus Business Park,
Herald Way,
Castle Donington,
Derbyshire
DE74 2TU

15. Glossary

Abbreviation	Term
DFES	Distribution Future Energy Scenario
DNO	Distribution Network Operator
DSO	Distribution System Operator
EAC	Estimated Annual Consumption
EV	Electric Vehicle
LCT	Low Carbon Technology
LV	Low Voltage
NESO	National Energy System Operator
NGED	National Grid Electricity Distribution
NIA	Network Innovation Allowance
PEA	Project Eligibility Assessment
PV	Photovoltaic
RMS	Root Mean Square
SMITN	Smart Meter Innovations and Test Networks (NGED Innovation project)
V2G	Vehicle-to-Grid

