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Opportunities to utilise vehicle to grid in accelerating decarbonisation of Scottish transport

Alexander Fish, Daisy Tyrer, Freddie Barnes, Celine Cluzel
ERM
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1 Executive summary

Smart charging involves charging electric vehicles (EVs) at times when demand for electricity and costs are lower. Vehicle-to-Grid (V2G) technology uses smart charging and also enables sending power from an EV back to a house and on to the national grid.

This study investigated V2G opportunities to accelerate the decarbonisation of transport in Scotland compared to smart charging alone. We reviewed global V2G projects to understand potential opportunities in Scotland and carried out modelling to quantify the potential for V2G to accelerate EV uptake.

1.1 Findings

The estimated net additional value (£ 2023) from V2G compared to smart charging can be calculated as the difference between the revenues from smart charging alone and additional value from V2G. The additional value to vehicle operators for five V2G opportunities we considered are shown in the table below:

Opportunity	Additional value (£/EV/year)
Domestic passenger cars	764
Vans in an urban depot	364
Trucks in an urban depot	788
Buses in an urban depot	0
RCVs in an urban depot	0

In general, we found that:

- The financial benefits for V2G are strongest for vehicles/fleets with low daily usage and that are charged spanning both peak and low electricity system demand times. However, smart charging without V2G could provide a significant proportion of the benefits that V2G can offer.
- Passenger cars' low usage relative to commercial fleets yields a strong V2G use case.
- Given that the benefits from V2G depend on infrastructure costs and battery degradation, a comprehensive approach is required to make EV adoption and decarbonisation more feasible.
- High additional value can be achieved from local flexibility services, where consumers are paid by local electricity network operators to adjust their demand, for vehicles such as passenger cars, but the value is highly location specific.
- V2G for commercial fleets would be more feasible by reducing vehicle usage and extending charging windows, which could conflict with their priority of ensuring service reliability.
- Across all vehicle types, a positive use case for V2G may not be sufficient to accelerate EV uptake. Other factors also influence the uptake of EVs, such as upfront costs. V2G further increases the upfront investment required despite adding value in the longer term.

1.2 Findings for use cases

Specific findings for the three use cases considered in detail in this report with potential additional value included:

- **Domestic passenger cars:** If V2G installation and maintenance costs remain high in the future, drivers of domestic passenger cars could consider installing V2G solutions from 2025 if they are located in constraint managed zones (area of existing electricity network where network requirements related to the security of electricity supply are met through the use of flexible services), where they will be able to access financial benefits from local flexibility services. Consumers in other parts of Scotland should wait until 2030 before installing V2G solutions. However, if costs of adopting V2G are low, there could be a valuable use case for domestic passenger cars across Scotland from 2025.
- **Vans:** V2G could be beneficial to vans between 2025 and 2030 if costs of V2G adoption are low or battery degradation from V2G is minimal.
- **Trucks:** Truck fleet operators are expected to benefit from V2G if low-cost hardware becomes available and battery degradation and maintenance costs are low. High upfront investment could be paid back from 2030 if battery degradation is well managed.

1.3 Conclusion

To conclude, accelerated decarbonisation of road transport could be achieved from investment in V2G solutions targeting domestic passenger cars and fleet operators with vehicles that do not have high daily usage and have long overnight charging windows.

Future work and research could focus on removing the barrier of the high upfront infrastructure cost, supporting wider access to flexibility services, and improving understanding and management of battery degradation.

Contents

2 Glossary and abbreviations

Glossary

Balancing Mechanism	The Balancing Mechanism is used by National Grid ESO to balance supply and demand on Great Britain's network. It is used to obtain electricity required to balance the electricity system. This is done on a second-by-second basis, to balance supply and demand in real time.
Calendar degradation	Battery capacity (amount of energy that can be stored) degrades due to both calendar degradation and cycling degradation. Calendar degradation occurs from a fade in battery capacity over time.
Constraint management zone	A constraint management zone (CMZ) is an area of existing electricity network where network requirements related to security of electricity supply are met through the use of flexible services, such as Demand Side Response, energy storage, and stand-by generation. Both Scottish and Southern Electricity Networks (SSEN) and Scottish Power Energy Networks (SPEN), the two distribution network operators in Scotland, define CMZs in their license areas where they procure flexibility services to mitigate or delay network upgrades.
Curtailment	Curtailment refers to a user's ability to import from or export to the network being restricted. When this occurs the user's access to the network is said to be curtailed. This is particularly used in the context of renewables generation, for example, curtailment may occur on a wind farm as a partially or totally imposed power reduction when the grid cannot absorb all the produced power.
Cycling degradation	Battery capacity (amount of energy that can be stored) degrades due to both calendar degradation and cycling degradation. Cycling degradation occurs due to the use of the battery (number of charging and discharging cycles).
Demand flexibility service	The demand flexibility service (DFS) allows participants to gain additional value for shifting electricity usage outside of peak demand hours.
Distribution system operator	A distribution system operator (DSO) is an entity responsible for distributing and managing energy from the generation sources to the final consumers. DSOs typically provide electricity from the grid to homes and businesses. In Scotland, the DSOs are SSEN and SPEN.
Electricity system operator	The electricity system operator (ESO) is the body which balances supply and demand of electricity across the high

	voltage grid. It is in charge of moving high voltage electricity from where it's generated through the transmission grid network to the demand centres across the UK.
Energy arbitrage	Participants buy power at off-peak hours, storing it and discharging during peak hours when grid prices are highest.
Energy markets	Energy markets allow electricity to be traded across the network such that electricity supply adequate to meet demand. Within the UK, there are key markets such as the wholesale market, retail electricity market, balancing mechanism market and balancing services market.
Local constraint market	Local constraint market (LCM) can be used to effectively manage grid constraints and optimise the utilisation of renewable energy resources by offering both turn-up and turn-down actions. In Scotland, the LCM rewards participants for turning up their electricity consumption in order to use excess wind energy generation. It is designed for managing constraints on the grid caused by peak wind energy generation. The LCM is currently being trialled by ESO and is targeting domestic and commercial customers.
Rigid truck	A rigid truck is a small to medium sized HGV whereby the chassis forms both the tractor and the trailer. In this study, we assume the typical size of a rigid truck is 7.5 – 32 tonnes, with a small number of extreme exceptions. We assume they are commonly used for applications such as last mile distribution to stores (typically 18t or 26t rigid)
Smart charging	Smart charging involves charging EVs at times when demand for electricity is lower, for example at night, or when there is lots of renewable energy on the grid. Charging during off-peak times reduces costs by using cheaper energy rates and helps reduce periods of high demand for electricity.
Stacking	Combining revenue streams from different energy markets, such as the Balancing Mechanism and the DFS to maximise the overall use case.
Total cost of ownership	The total cost of ownership (TCO) is determined from the costs and financial value over the lifetime of a product. It establishes a standardised way to compare costs for products over time.

Abbreviations

AC	Alternating current
CMZ	Constraint management zone
DC	Direct current
DFS	Demand flexibility service
DSO	Distribution system operator
ESO	Electricity system operator
EV	Electric vehicle
GHG	Greenhouse gas
HGV	Heavy goods vehicle
LCM	Local constraint market
LGV	Light goods vehicle (<3.5t)
RCV	Refuse collection vehicle
SPEN	Scottish Power Energy Networks
SSEN	Scottish & Southern Electricity Networks
V2G	Vehicle-to-grid

3 Introduction

3.1 Context

The Scottish government has set ambitious climate change targets. They aim to reduce emissions by 75%, 90%, and 100% compared to 1990 levels by 2030, 2040, and 2045, respectively [1]. Transport is Scotland's largest source of emissions and in 2021, road transport accounted for 75.5% of total transport emissions (including international aviation and shipping)[1] [2]. A significant reduction in emissions from the road transport sector will be necessary for Transport to meet its emissions envelope with a rapid transition to zero emission vehicles vital to achieving net zero targets.

Although charging of EVs is currently cheaper than the cost of refuelling Internal Combustion Engine (ICE) vehicles, EV owners and fleet operators are becoming increasingly exposed to the cost of electricity during charging [3]. Innovative charging technologies such as smart or bidirectional charging can play a crucial role in Scotland by further lowering refuelling costs for EVs, with smart charging optimising demand to make the most of low electricity prices and bidirectional charging financially rewarding EVs for discharging into the grid. As such, both smart and bidirectional charging may have the potential to accelerate the pace of transport decarbonisation, lessening impacts of electrification on the power system or even providing net benefits. However, the higher upfront costs and low commercial availability of V2G may act as barriers to adoption.

V2G technology enables the bidirectional charging of EVs, allowing them to charge and discharge energy back to the grid. This capability enables EVs to participate in energy markets and provides wider system benefits to help support the grid during periods of peak electricity demand or supply.

3.2 Objectives of the study

The core objective of this study is to understand whether V2G presents opportunities to accelerate the decarbonisation of transport in Scotland, by assessing the potential for V2G to accelerate EV adoption in Scotland.

In this study, we review global V2G projects to understand potential opportunities in Scotland and carry out modelling to quantify the potential for V2G to accelerate EV uptake. Alongside this, we consider the barriers and opportunities to adoption of V2G through engagement with key stakeholders. Full detail on our methodology is set out in Appendix 11.

[1] The total volume of Scottish Transport emissions remains lower than it was in 2019, pre-pandemic.

4 Assessment of V2G opportunities

4.1 Review of global V2G trials

A database of V2G trials was generated from a global literature review, setting out the opportunities examined, the transport sector, geographic location, and context, as well as additional information on duty cycles – the database and summary of the 23 identified trials is shown in Appendix 10.1.

From the global trials, we conclude that:

1. V2G is technically feasible for passenger cars [4], buses [5], and vans [6].
2. V2G would be able to provide grid services to help support Distribution Network Operators (DNOs) across the United Kingdom [7], Europe [4] and North America [8].
3. V2G can offer monetary value for EV owners who can be financially rewarded for discharging electricity back into the grid. The ongoing revenue from the discharged electricity can help lower the total cost of ownership (TCO) of the EV [9].
4. Barriers for V2G rollout include the initial capital cost for charging hardware and installations [9] as well as the timeline and requirements for establishing a grid connection [10].

4.2 Assessment of benefits

V2G can offer electricity system and financial benefits by allowing vehicles to participate in energy markets. These benefits can help to alleviate congestion on the electricity grid and reduce carbon emissions from high carbon technologies and through the incentivisation of fleet electrification.

Potential benefits were assessed considering suitability for V2G participation and the financial value for V2G participants. More detail on the potential benefits can be found in Section 10.3 and summarised in Table 1.

Scotland presents unique V2G opportunities owing to the constraint on the transmission network between Scotland and England, as well as local limitations within Scottish & Southern Electricity Networks (SSEN) and Scottish Power Energy Networks (SPEN) networks. Newly introduced flexibility services targeting domestic and commercial consumers, like the Demand Flexibility Service (DFS) and Scotland's Local Constraint Market (LCM) may offer short-term advantages. As they specifically target small-scale consumers/generators, such as EVs, the DFS and LCM have lower barriers to entry than other flexibility markets, such as the Balancing Mechanism. Therefore they could offer value for V2G in the short-term, while access to other flexibility markets is still prohibitive. However, participating in these services in the long term could limit the potential value of V2G as the barriers to enter other flexibility markets are overcome.

Currently, it is not possible to participate in the DFS or LCM alongside other flexibility services, such as the Balancing Mechanism, which can generate assets more value over the course of the year. Although it is possible that this restriction will be lifted in the future to allow participation in these markets alongside other flexibility markets, it is not confirmed and the required conditions are not clear. As a result, in the short term V2G could access value from participating in the consumer-targeted services such as the DFS and LCM.

However, it is not clear if participation in these markets will be valuable in the long-term, as consumers may be able to make more revenue in the future from participating in a combination of other flexibility services, such as the Balancing Mechanism.

	Benefit	Description	V2G participation suitability	Value from V2G	Overall assessment
ESO service	Frequency response	Service to manage the second-by-second change in demand or supply on the electricity grid. Product names include Dynamic Containment.	Low	Participation not possible, so no value	Low overall suitability and will not be considered in modelling
	Balancing Mechanism	Service to obtain the right amount of electricity required to balance the electricity system in each half-hour trading period of every day. Used to increase or decrease generation or consumption.	Medium	High	Medium/high suitability but some access limitations. Will be modelled
	Reserve	Additional power sources which are used to balance the electricity system. They balance the system and control frequency over longer timescales than frequency response.	Medium	Medium	Medium overall suitability and will not be considered in modelling
	Demand flexibility service	Participants (domestic and commercial) can earn financial rewards for shifting electricity usage outside of peak demand hours.	High	Medium	Medium/high suitability for both domestic and commercial participants
	Local constraint market	**Scottish specific** service to incentivise demand turn up/generation turn down to reduce transmission network constraints.	High	Medium	Medium/high suitability and Scotland specific, will be modelled
DSO service	DSO flexibility service	DSO procured services to prevent network congestion within a local area. In Scotland, these are procured in CMZs.	High	High	High overall suitability. Will be considered in modelling.
Other	Energy arbitrage	Participants can sell electricity (discharge) back to the grid during periods of high prices and to buy electricity (charge) when prices are lower.	High	High	High overall suitability. Will be considered in modelling.
	Integration of on-site RES	Participants can optimise self-consumption, reducing grid electricity purchases and selling excess electricity at high prices.	High	Medium	Medium/high overall suitability. Will be modelled.

Table 1: ESO, DSO and other financial benefits graded by their suitability for V2G participation, value and includes an overall assessment. The grading uses a red, amber, and green scale, defining low, medium and high V2G participation suitability and value from V2G, respectively.

4.3 Assessment of costs

4.3.1 Cost of chargers

V2G business models currently incur higher costs relative to smart chargers. Smart chargers are unidirectional and are able to intelligently manage how much energy to give to a plugged-in EV. This study considers smart charging as the baseline case, as smart charging is assumed to be the standard in the UK, considering the Electric Vehicles (Smart Charge Points) Regulations 2021, which stipulates that electric chargers sold in Great Britain must have smart functionality [11]. In contrast, the greater functionality of bidirectional chargers (used for V2G), which can feed energy into the grid, incurs higher costs mainly due to increased hardware and installation expenses, along with added battery degradation and maintenance costs. More detail on the potential costs can be found in Section 10.4.

There is limited data on the cost of V2G chargers in literature, although estimates can exceed twice the cost of smart EV chargers, with smart chargers costing £1,400 and V2G chargers costing £4,160, as shown in Figure 1 [12].

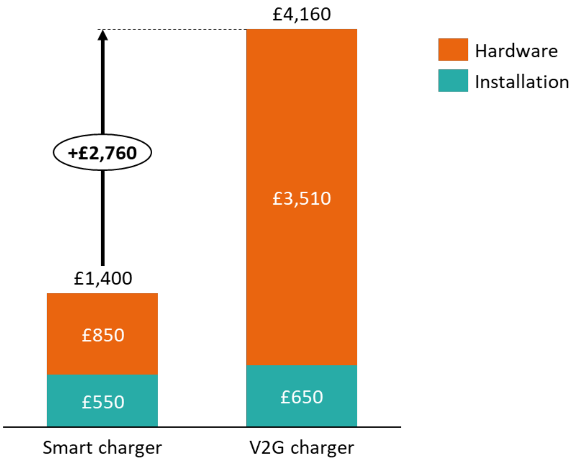

Figure 1: Estimated hardware and installation costs (£ 2023) for a smart charger compared with a DC bidirectional charger. These have been calculated from data in the literature [12].

4.3.2 Battery degradation

Research is currently ongoing to assess the impact of bidirectional charging on battery degradation, with the exact effect still uncertain. Battery degradation includes both cycling and calendar fade. Cycling degradation of a battery occurs due to the use of the battery (number of charging and discharging cycles) while calendar degradation occurs from a fade in capacity over time. Calendar degradation can be further exacerbated by leaving the battery at 0% or 100% charge [13].

Most studies suggest that V2G systems may accelerate degradation, mainly due to the increased annual cycling of batteries (cycling degradation rather than calendar degradation) [13]. The extent of this cycling depends on the charging and discharging cycles of the batteries. This degradation can lead to a reduction in an EV's range and potentially necessitate battery replacement during the vehicle's lifespan, which represents an additional cost and might discourage consumers.

Conversely, some sources propose that V2G systems could preserve battery state of health [14]. Calendar degradation is directly influenced (along with other factors) by the state of charge at which the battery is held. Bidirectional charging, along with proper battery management strategies, can help mitigate calendar degradation by maintaining the state of of charge of the battery at a more optimal value. This could balance the effect of increased cycling from V2G, and potentially prolong the battery life.

To account for the ongoing research to understand the impact of bidirectional charging on battery degradation, two scenarios were modelled to represent the cost of increased battery degradation as a result of V2G, expressed as a cost per MWh discharge. Full details of the findings on battery degradation can be found in Appendix 10.4.2.

5 Analysis of V2G use cases

5.1 V2G use cases

Rankings based on emissions contribution, fleet size, and financial savings and other benefits were used to determine the opportunities with the biggest impact (Table 2). These include passenger cars at home, vans in an urban depot, RCVs in an urban depot, rigid trucks in an urban depot and buses in an urban depot. The use cases are assumed to be within an urban environment due to the likely value of local constraint alleviation and the expected duty cycles.

Further details on the assessment of opportunities can be found in Section 10.2. The detailed development of each use case, including modelled carbon emissions savings from a fully electrified fleet, expected infrastructure costs and projected additional value, is set out in Section 6. Furthermore, priority areas were aligned with Transport Scotland which informed the final selection of the five use cases.

Use case	**Emissions impact** (2021 [2])	**Scale of fleet in Scotland** (2021 [63])	**Benefits available**
Passenger cars at home	**High** - Passenger cars are responsible for 53% of Scottish road transport emissions	**High** - 2.52m passenger cars registered	**High** - Grid services, Energy arbitrage, Integration of on-site renewables
Vans in an urban depot	**Medium** - LGVs were responsible for 20% of Scottish road transport emissions	**Medium** - 192,000 registered LGVs in an urban context	**High** - Grid services Energy arbitrage
Trucks in an urban depot	**Medium** – HGVs were responsible for 21% of Scottish road transport emissions	**Medium** - 22,000 registered HGVs in an urban context	**High** - Grid services, Energy arbitrage, Integration of on-site renewables
Buses in an urban depot	**Low** - Buses were responsible for 1% of road transport emissions	**Medium** - 9,230 registered buses in an urban context	**High** - Grid services, Energy arbitrage
RCVs in an urban depot	**Low** – RCVs in Scotland are estimated to be reponsible for 0.25% of Scottish road transport emissions[2]	**Low** - 22,000 registered HGVs in urban context & an estimated 1,250 RCVs registered in Scotland	**High** - Grid services, Energy arbitrage

Table 2: Five use cases selected on basis of V2G opportunities in Scotland. Selection based on road transport emissions [15, 16, 17], registered passenger vehicles [18], and available benefits.

[2] The emissions from RCVs were estimated using the total emissions from RCVs in the UK and the estimated percentage of RCVs in registered in Scotland [16, 31]

5.2 Charging behaviour

A combination of data from literature and stakeholder engagement was used to determine the potential battery capacity available and timeframe for V2G participation. Data is based on average daily charging demand, battery size, and charging windows. A summary of the assumed charging demand for each use case is shown in Figure 2, and the charging window is shown in Figure 3.

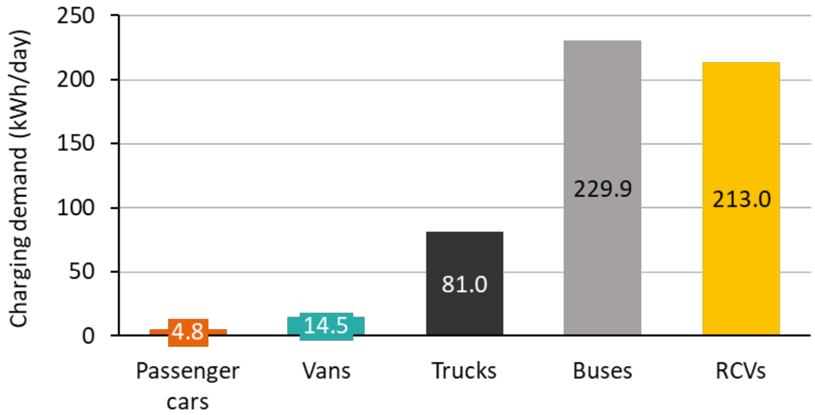

Figure 2: Daily charging demand of different vehicle types (kWh/day) modelled for each use case [19, 20, 21, 22, 23].

As shown in Figure 2, passenger cars and vans are modelled as having the lowest daily charging demand at 4.8 kWh/day and 14.5 kWh/day respectively. They also have similar charging windows, with cars plugging in between 5.30pm and 8am and vans plugging in between 7pm – 8.30am, as shown in Figure 3.

Buses are modelled as having the highest daily charging demand at 229.9 kWh/day, and have the shortest charging window of 5.5 hours, as shown in Figure 3. RCVs have the longest plug-in time of 15.5 hours, but also the second highest daily charging demand of 213 kWh/day. Trucks have a moderately high charging demand of 81 kWh/day as shown in Figure 2, but a long overnight charging window of 12 hours.

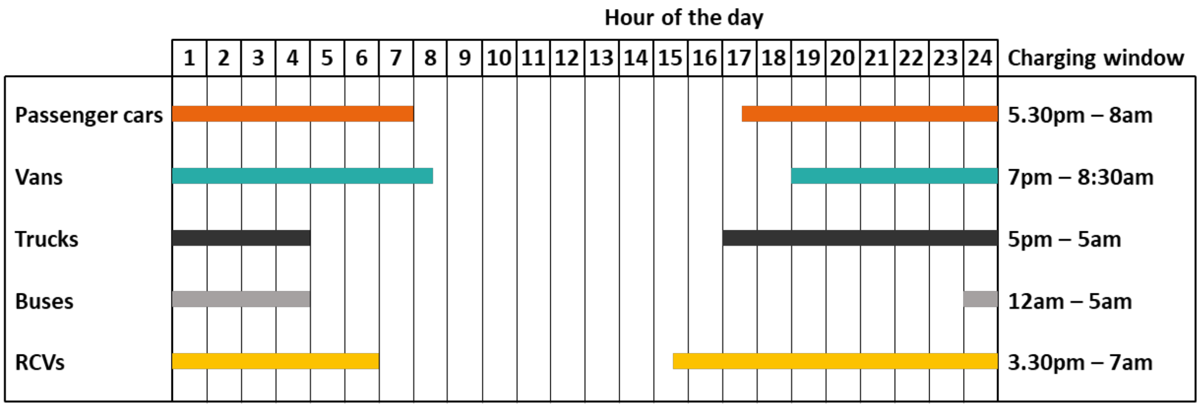

Figure 3: Assumed hourly breakdown of the charging windows for each use case. A full line indicates when the respective vehicles are plugged in and can participate in V2G [24, 25, 26].

5.3 Additional value from V2G

The charging profiles for each use case were modelled to understand the additional value that can be achieved with either smart charging alone or with V2G. In the same way that smart chargers have been chosen as a baseline for the costs, smart charging has been chosen as a baseline for determining the additional value from V2G (as per the charging smart charging regulations).

The modelled additional value was calculated considering the availability of:

1. Energy arbitrage (considering electricity prices on the wholesale market) and the Balancing Mechanism, in addition to on-site renewable generation.
2. Local flexibility services for the DNO.
3. Consumer flexibility services, including the DFM and Scotland's LCM. It should be noted that consumer flexibility services cannot currently be stacked with the Balancing Mechanism.

Further detail on the method for modelling of the additional value can be found in Appendix 11. The modelled additional value compared to smart charging for each of the five use cases when participating in V2G is shown in Figure 4.

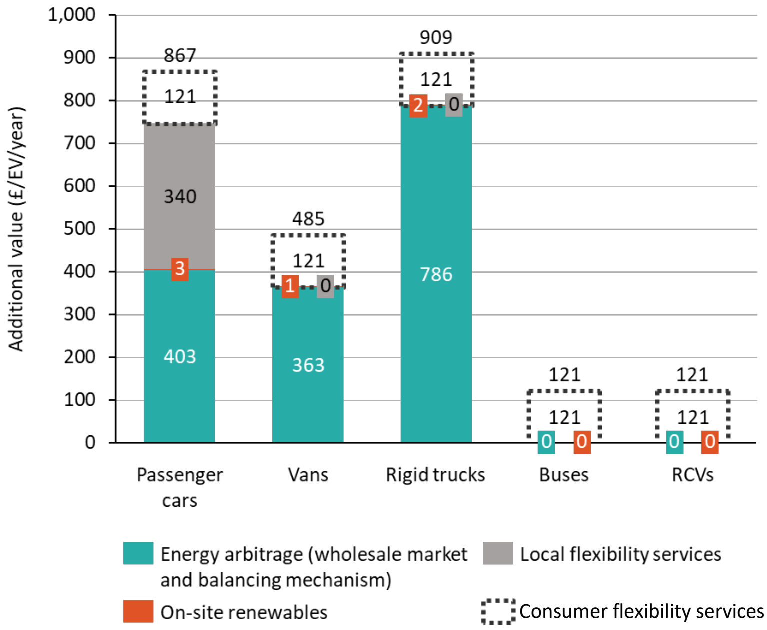

Figure 4: Modelled additional value (£ 2023) for each use case from V2G broken down by financial benefit.

For buses and RCVs, the additional value achieved with V2G compared with smart charging is only generated through participation in consumer flexibility services. Electric buses and RCVs generate significant revenue from the Balancing Mechanism when smart charging but is not able to generate further Balancing Mechanism revenues through V2G.

As shown in Figure 4, passenger cars, vans and trucks generate the majority of additional value from V2G through energy arbitrage, considering both the wholesale electricity market and the Balancing Mechanism. Passenger cars are able to generate further additional value through participation in local flexibility services. While all use cases are modelled to participate in local flexibility services through smart charging alone, only passenger cars have sufficient battery capacity at the beginning of their charging window to discharge over the evening peak required for local flexibility services.

Modelling of the additional value showed that participation in flexibility services with smart charging alone produced significant additional value for all use cases. This is detailed further in Section 6.

6 Deep dive on the use cases

6.1 Use case 1: Domestic passenger cars

Passenger cars were selected as a use case offering V2G at home. Passenger cars comprise 82% of Scotland's road vehicle fleet and contributed 53% of road emissions in 2021, making them the most significant vehicle type in both categories [15]. Electrifying this fleet in Scotland would lead to significant carbon emissions savings, amounting to a total reduction of 4.62 $MtCO_2$ as shown in Figure 5.

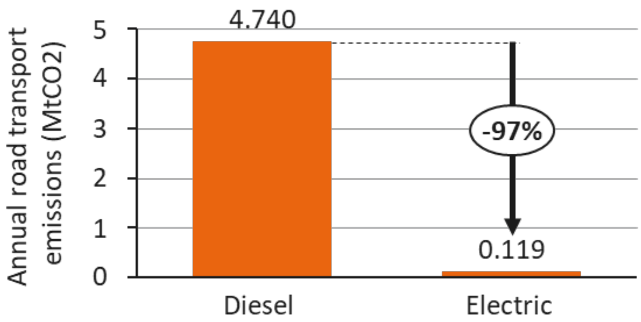

Figure 5: The reduction in carbon emissions from road transport from a fully electric fleet of passenger cars in Scotland.[3]

The estimated daily energy use for passenger cars is 4.8 kWh, leaving 46.2 kWh of available energy for V2G participation (Appendix 11.5.1). Figure 6 illustrates the average charging profile for passenger cars, with a charging window from 5:30 pm to 7:30 am.

[3] Calculated from the total road transport emissions and the percentage from passenger cars [2]. Emissions savings are determined assuming the entire fleet is electrified and charges using a grid intensity of 26.9 gCO_2/kWh [84].

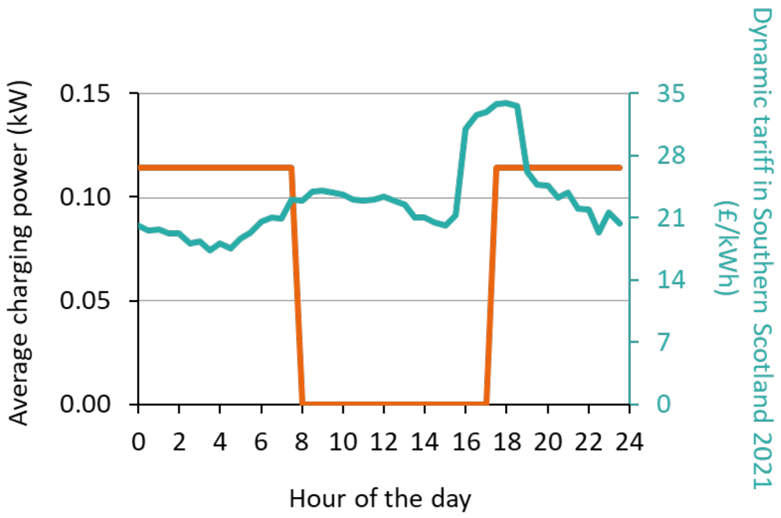

Figure 6: Showing the average charging power and timeline for when the electric passenger car is plugged in [24] along with a dynamic tariff in Southern Scotland [27].

Figure 7 displays the modelled additional value from energy arbitrage and participation in flexibility services, showing that V2G generates higher value compared to smart charging alone. Passenger cars using V2G can gain additional value by discharging during evening hours and recharging when electricity prices are at their lowest, typically between 12 am and 4 am.

The additional value potential of V2G for passenger cars is predominantly from energy arbitrage and local flexibility services. Given their specific duty cycles and plug-in times, passenger cars offer a substantial surplus of energy when plugged in overnight, which can be used for engagement in wholesale energy arbitrage, the Balancing Mechanism and local flexibility markets. If in the future consumers are able to access consumer flexibility services, including the Scotland specific LCM, alongside other flexibility services they may be able to access a small amount of further additional value.

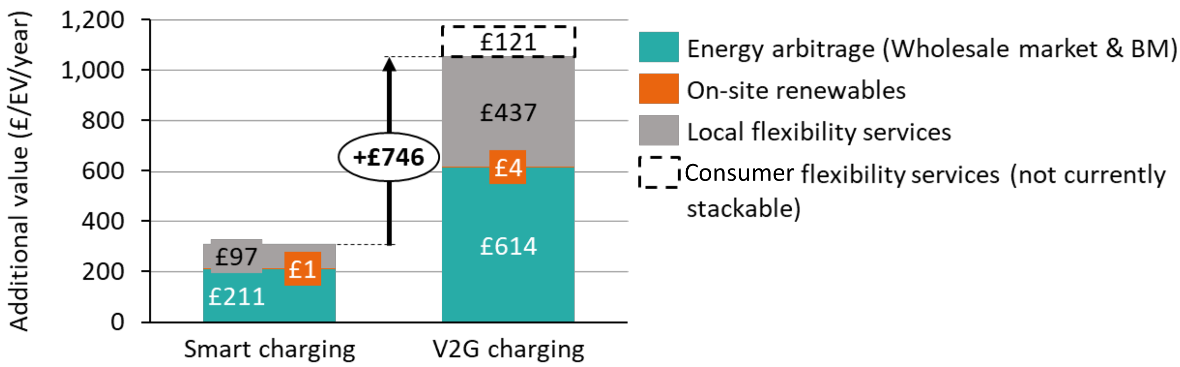

Figure 7: Composition of modelled additional value (£ 2023) to consumers for both smart charging and V2G charging for passenger cars. Note: dotted box shows the potential additional value from participation in Consumer flexibility services if in the future these could be stacked alongside other flexibility services.

Figure 8 shows the hardware and installation costs of V2G chargers, these have been modelled within a high or low-cost scenario which is described in further detail in Section

11.5.3. Passenger cars are assumed to use a 7-kW charger, which is lower cost than higher-power chargers.

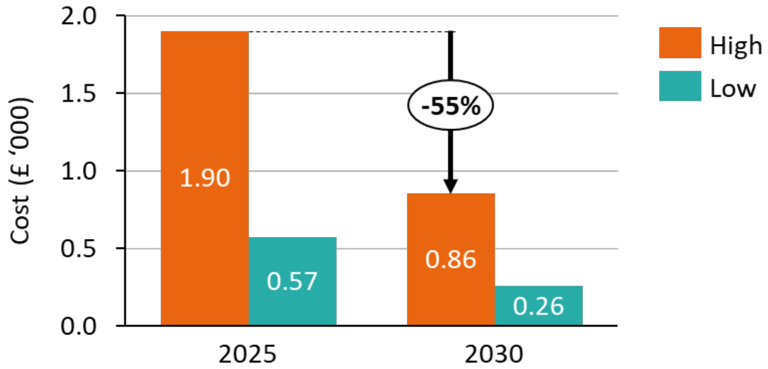

Figure 8: Associated costs (£ 2023) for hardware and installations for a 7 kW AC charger in 2025 and 2030.

Passenger cars participating in V2G services could stimulate EV uptake due to the financial advantages they offer while simultaneously delivering net system benefits through local and consumer flexibility services during peak demand. **There is a strong case for passenger cars to participate in V2G under the assumptions considered.**

6.2 Use case 2: Vans in an urban depot

Vans fall into the category of LGVs which comprised 11% of registered vehicles in Scotland in and contributed to 20% of Scottish road-based emissions in 2021. The urban context was chosen as approximately 58% of LGVs in Scotland were situated in urban areas in 2021 [18] [28].

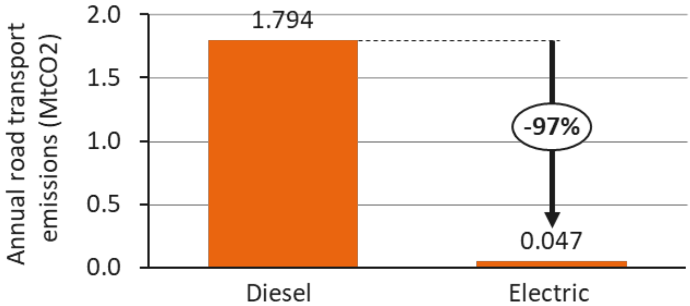

Figure 9: The reduction in carbon emissions from road transport from a fully electric fleet of LGVs in Scotland.[4]

Figure 9 shows the carbon emissions savings achievable from a fully electrified van fleet, resulting in a total reduction of approximately 1.75 $MtCO_2$.

[4] Calculated from the total road transport emissions and the percentage from LGVs [2]. Emissions savings are determined assuming the entire fleet is electrified and charges using a grid intensity of 26.9 gCO_2/kWh [84].

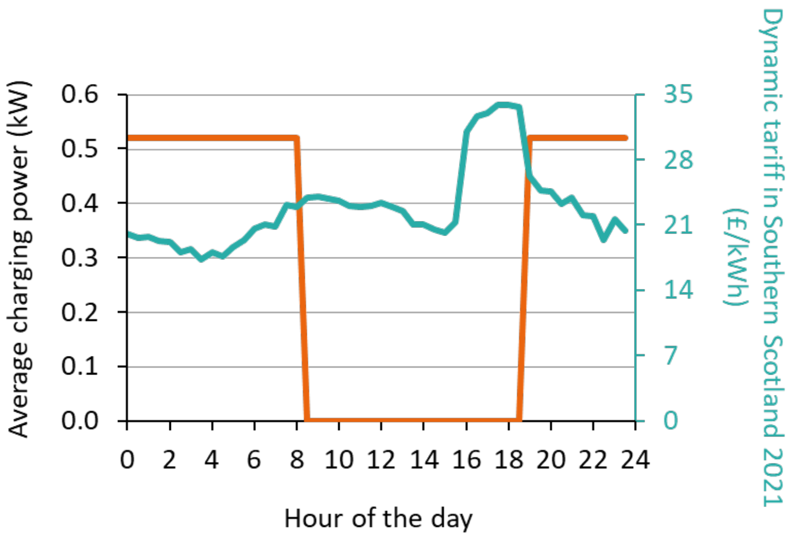

Figure 10: The average charging power and timeline for when the electric van is plugged in [28] along with a with a dynamic tariff in Southern Scotland [27].

Figure 10 shows the average charging power profile for vans. The charging window is from 7 pm to 8:30 am (UK Power Networks, 2022). The average daily energy consumption for vans is estimated at 14.5 kWh, calculated from average daily mileage and electricity consumption data provided in Appendix 11.5.1.

As shown in Figure 11, V2G participation for vans offers a source of moderate additional value as their duty cycles allow them to engage in both wholesale electricity market and the Balancing Mechanism through energy arbitrage overnight. However, modelling shows that the electric van battery would be expected to be almost depleted when plugging in, thus they are unable to offer local flexibility services over the evening peak. If in the future consumers are able to access consumer flexibility services, including the Scotland specific LCM, alongside other flexibility services they may be able to access a small amount of further additional value.

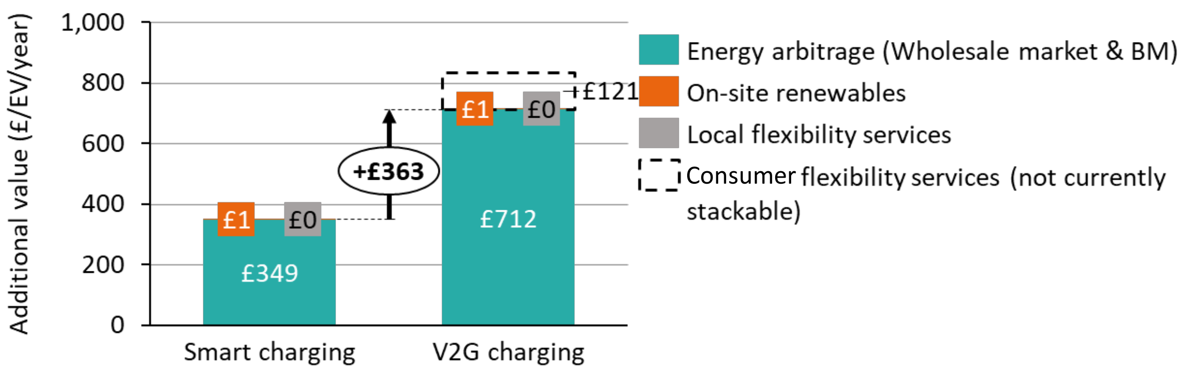

Figure 11: Composition of modelled additional value (£ 2023) to consumers for both smart charging and V2G charging for vans.

The cost of hardware and installation of V2G chargers, as shown in Figure 12, is the same as that for passenger cars, assuming a 7 kW AC charger. The costs have been modelled within a high or low-cost scenario which is described in further detail in Section 11.5.3

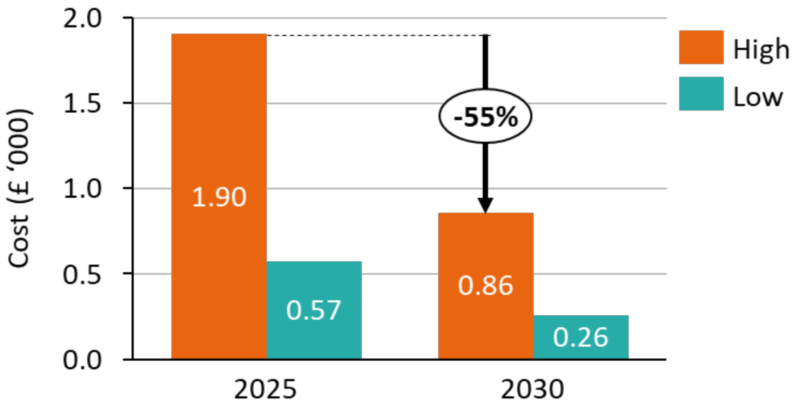

Figure 12: Associated costs (£ 2023) for hardware and installations for a 7 kW AC charger in 2025 and 2030.

Electric van fleets across the UK are expected to have highly varied duty cycles with differences in mileage, operating radii, and charging opportunities [29] and therefore will have differing opportunities to benefit from V2G. Furthermore, fleet operators may currently be apprehensive to adapt their operating schedules to participate in V2G. However, if V2G is able to provide ongoing revenues to fleets, this may encourage operators to electrify their fleets by reducing the total cost of ownership [26].

Additionally, findings indicate that the costs of hardware and installation pose significant barriers for small firms with limited resources to invest upfront in charging infrastructure and electric vehicles [29]. Further findings from this study highlighted that vans that charged at home, especially those belonging to small businesses, are likely to face higher prices to charge their EV. V2G will require higher upfront investment, however, the additional value for participation in V2G could help to reduce both the cost of charging and transition.

With the assumptions made here, V2G participation is likely to provide financial benefits, given the duty cycles of vans in urban environments. However, the additional upfront cost of infrastructure could be a barrier.

6.3 Use case 3: Trucks in an urban depot

Rigid trucks fall within the vehicle category of HGVs. These vehicles constituted 1.2% of registered vehicles in Scotland in 2021, contributing to about 21% of Scottish road-based emissions in 2021 [18]. The urban context was chosen given that approximately 61% of HGVs in Scotland were situated in urban areas in 2021 [30]. Figure 13 shows the potential carbon emissions savings from a fully electrified fleet of rigid trucks, estimated at approximately 1.80 MtCO2.

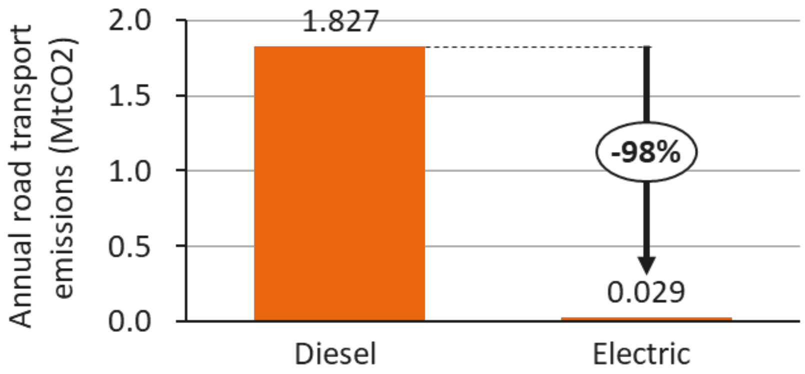

Figure 13: The reduction in carbon emissions from road transport from a fully electric fleet of HGVs in Scotland.[5]

Figure 14 illustrates the average charging power profile for an urban rigid truck, with a charging window spanning from 5 pm to 5 am [25]. The average daily energy consumption for these trucks is estimated at 81 kWh, calculated from average daily mileage and electricity consumption data in Appendix 11.5.1. The remaining available battery capacity, coupled with the charging window, creates an opportunity for the truck to participate in V2G upon its return to the depot for charging, as shown in Figure 14.

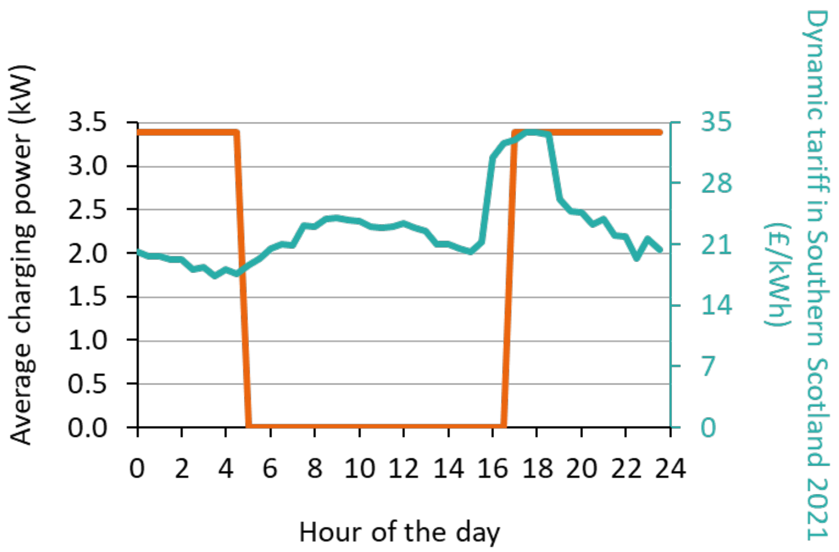

Figure 14: The average charging power and timeline for when the electric truck is plugged in [25] with a dynamic tariff in Southern Scotland [27].

As shown in Figure 15, the additional value from V2G is mainly from energy arbitrage, including wholesale market and Balancing Mechanism participation. The additional value from on-site renewables is negligible when comparing smart charging and V2G charging. If in the future consumers are able to access consumer flexibility services, including the

[5] Calculated from the total road transport emissions and the percentage from HGVs [2]. Emissions savings are determined assuming the entire fleet is electrified and charges using a grid intensity of 26.9 gCO_2/kWh [84].

Scotland specific LCM, alongside other flexibility services they may be able to access a small amount of further additional value.

Rigid trucks are assumed to use a 22 kW AC charger. Projections for the costs of hardware and installation for such chargers in 2025 and 2030 are displayed in Figure 16.

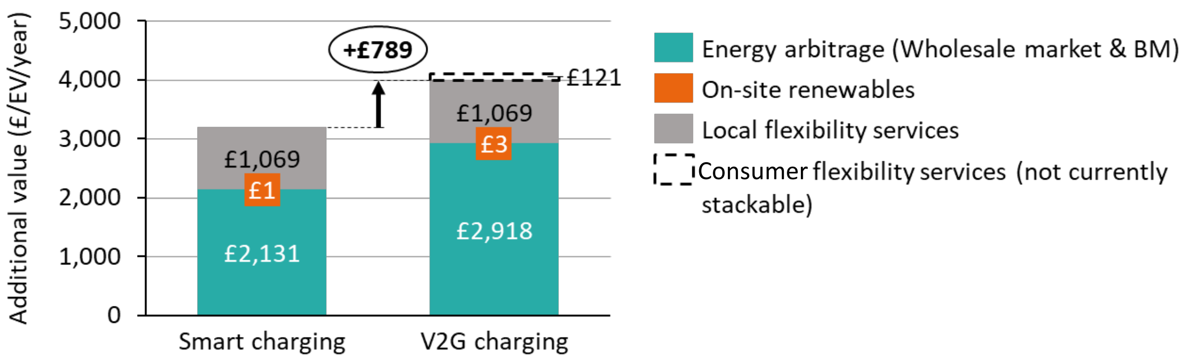

Figure 15: Breakdown of modelled additional value (£ 2023) for trucks for both smart charging and V2G.

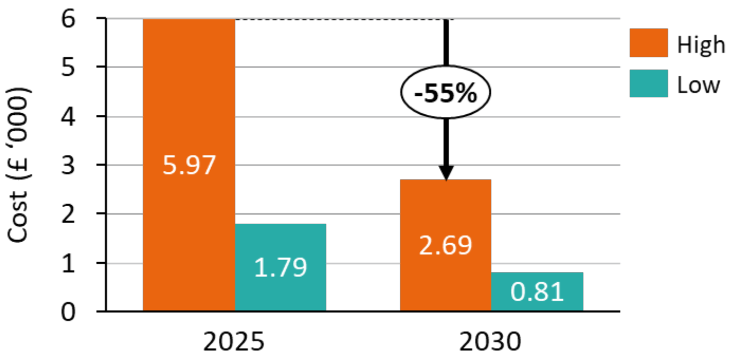

Figure 16: Associated costs (£ 2023) for hardware and installations for a 22 kW AC charger in 2025 and 2030.

While a positive use case for V2G could incentivise the electrification of trucks, insights from stakeholder engagement sessions suggest that truck fleet operators tend to prioritise high utilisation of their trucks to maximise revenues from existing operations. V2G would be viewed as a secondary priority and may not align with the primary business model.

Further barriers to V2G adoption are associated with the costs of V2G installations and the necessity for grid upgrades to support V2G. Stakeholder discussions indicated these investment costs to be approximately £350,000 (£ 2023), which serves as a significant hurdle for the widespread uptake of V2G.

While V2G participation has the potential to incentivise electric vehicle adoption, the incompatibility between duty cycles and charging requirements decreases the use case of V2G decarbonisation of emissions for the Scottish truck fleet.

6.4 Use case 4: Buses in an urban depot

In 2021, buses accounted for 1.2% of road-based emissions in Scotland [2] while approximately 71% of buses in Scotland were located in urban areas in 2021 [15].

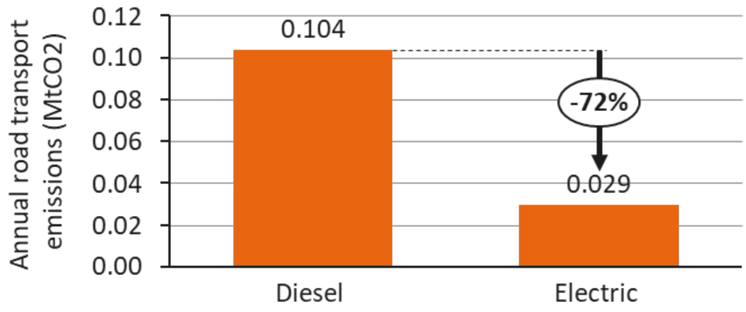

Figure 17: Reductions in carbon emissions from road transport from a fully electric fleet of buses in Scotland. [6]

Figure 17 shows the potential carbon emissions savings from a fully electrified fleet of buses, estimated at approximately 74 ktCO_2. Urban buses' daily energy use is estimated to be 230 kWh, as calculated from average daily mileage and electricity consumption in Appendix 11.5.1.

Figure 18 illustrates the average charging power profile for urban buses, with a charging window between 12 am and 5:30 am [25]. This charging window reflects the operation in a major German city and has been confirmed by a discussion with a major bus operator. The duty cycles of urban buses can be highly variable, ranging from 14 to 22 hours of daily use, making it difficult to model in terms of V2G.

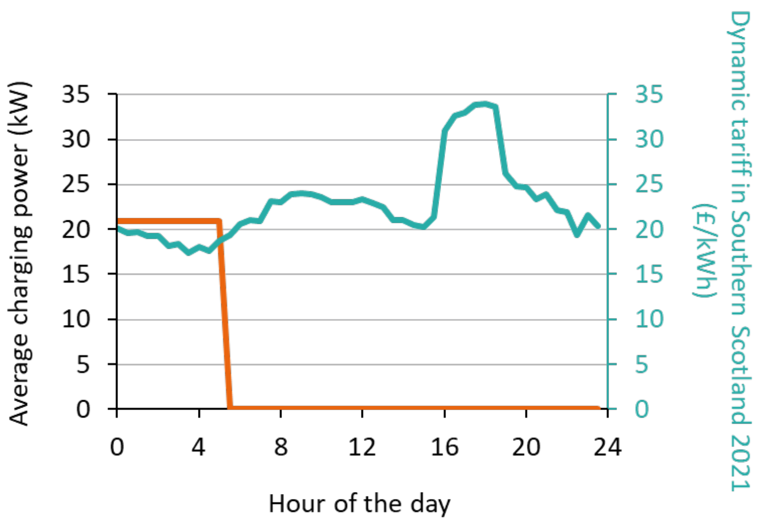

Figure 18: Average charging power and timeline for when the electric bus is plugged in [25] along with a with a dynamic tariff in Southern Scotland [27].

[6] Calculated from the total road transport emissions and the percentage from buses [2]. Emissions savings are determined assuming the entire fleet is electrified and charges using a grid intensity of 26.9 gCO_2/kWh [84].

The potential for additional value from V2G participation is significantly limited as the battery of an electric bus is expected to be depleted on return to the depot. This limits the capacity for V2G to take place over the charging window and leads to no additional value from V2G compared to smart charging alone, as shown in Figure 19. If in the future consumers are able to access consumer flexibility services, including the Scotland specific LCM, alongside other flexibility services they may be able to access a small amount of additional value from V2G.

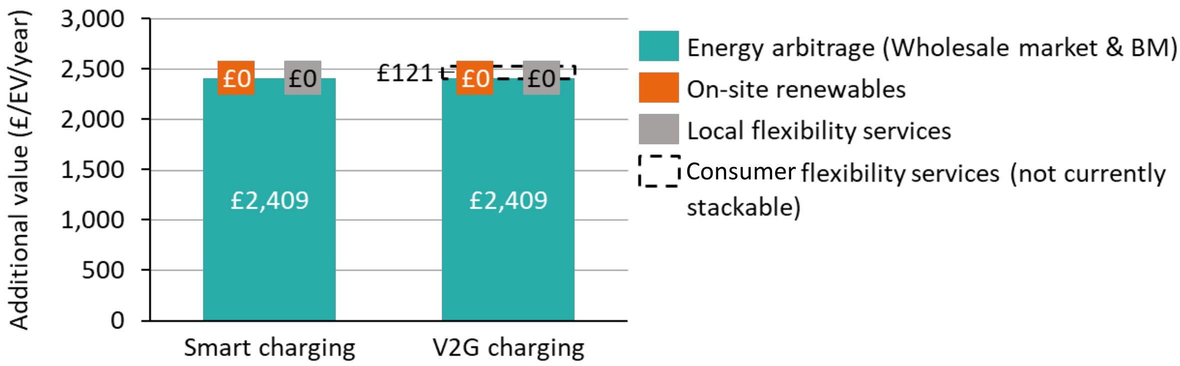

Figure 19: Breakdown of modelled additional value (£ 2023) from buses for both smart charging and V2G.

Longer plug in times were modelled for buses as a sensitivity. Within this sensitivity, an increased the plug-in time, from 8pm – 12am was found to have no impact on the additional value that V2G could offer.

V2G integration with buses is technically feasible, as shown in a previous proof-of-concept trial [5]. However, operational challenges arise, primarily ensuring that the buses are adequately charged for their respective duty cycles. To benefit from the potential additional value offered by V2G, bus operators may need to adjust duty cycles, including reducing daily mileage, to have more energy available for V2G participation. Such changes would impact the utilisation of the bus fleet, potentially affecting the existing business model of fleet operators.

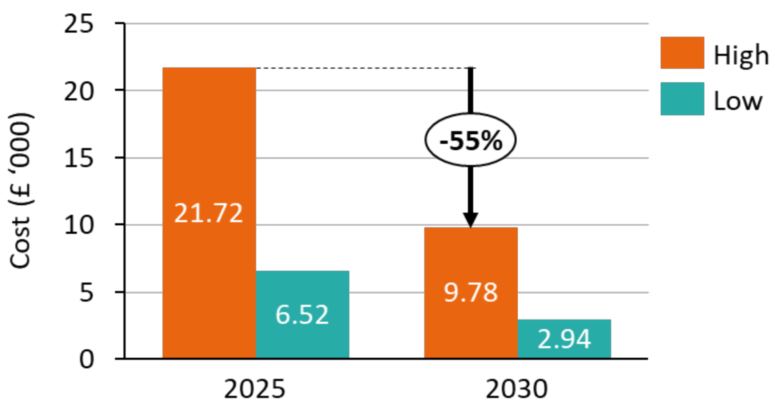

Figure 20: Associated costs (£ 2023) for hardware and installations for an 80 kW AC charger in 2025 and 2030.

As shown in Figure 20, the costs associated with hardware and V2G charger installation are influenced by the high power of the chargers, as buses are assumed to use an 80 kW AC charger. The higher charger power significantly escalates the hardware and installation costs. Cost reductions associated with charging hardware and installations are essential for the V2G use case.

While V2G participation has the potential to drive electric vehicle adoption, the incompatibility between duty cycles and charging requirements decreases the use case of V2G decarbonisation of emissions for the Scottish bus fleet.

6.5 Use case 5: RCVs in an urban depot

RCVs are classified as a type of HGV which represented 1.2% of registered vehicles in Scotland in 2021 and with an estimated contribution of 0.5% of road-based emissions in 2021 [15]. The urban setting was chosen because approximately 61% of HGVs in Scotland were located in urban areas in 2021 [30]. There are an estimated 1,246 RCVs in Scotland representing 7% of the UK fleet [31, 17]. The potential carbon emissions savings from a fully electrified RCV fleet are estimated at approximately 0.020 $MtCO_2$ as shown in Figure 21.

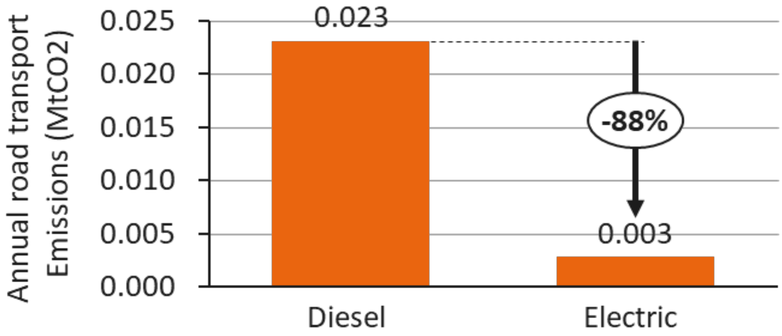

Figure 21: The reduction in carbon emissions from road transport from a fully electric fleet of RCVs in Scotland.[7]

Figure 22 shows the average charging power profile for RCVs, with a charging window spanning from 3:30 pm to 7 am [32, 25].

[7] Calculated from the total road transport emissions from RCVs in the UK [16] and determined in Scotland by the percentage of RCVs located in Scotland [17]. Emissions savings are determined assuming the entire fleet is electrified and charges using a grid intensity of 26.9 gCO_2/kWh [84].

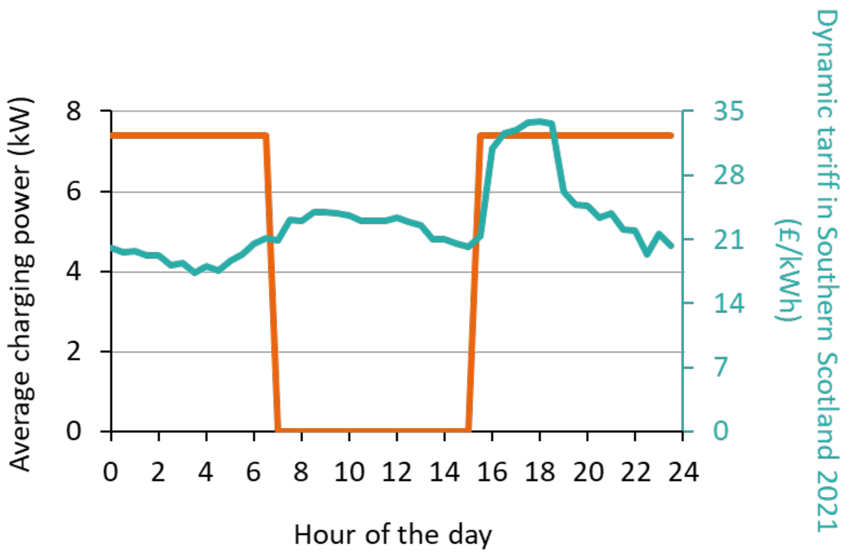

Figure 22: The average charging power and timeline for when the electric RCV is plugged in [25] along with a with a dynamic tariff in Southern Scotland [27].

The duty cycle of RCVs places limitations on the achievable additional value through participation in V2G markets, as shown in Figure 23. This is due to the energy intensity of the industry which is constrained by both mileage and uplift requirements for the waste collection service. When compared to passive charging, smart charging offers considerable value, however, V2G does not provide further value. If in the future consumers are able to access consumer flexibility services, including the Scotland specific LCM, alongside other flexibility services they may be able to access a small amount of additional value from V2G.

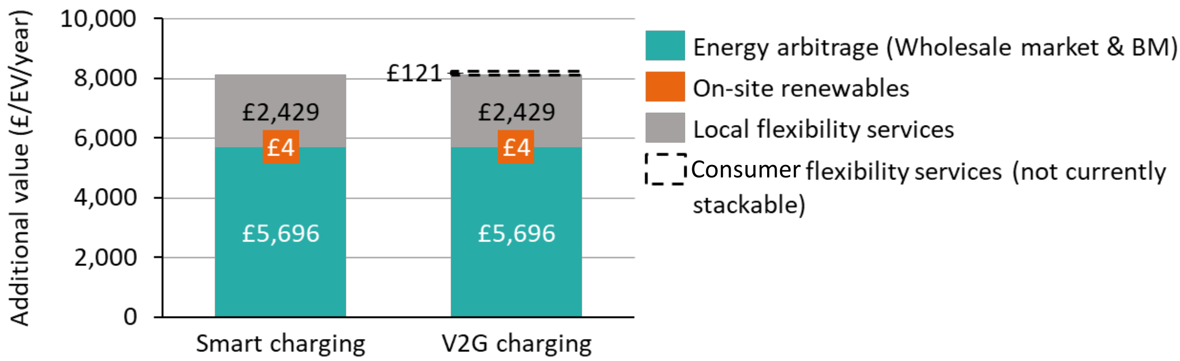

Figure 23: Breakdown of modelled additional value (£ 2023) for RCVS participating in both smart charging and V2G.

A charger power rating of 50 kW was assumed, as per stakeholder engagement with a Scottish City Council. This results in higher costs relative to slower chargers, as shown in Figure 24.

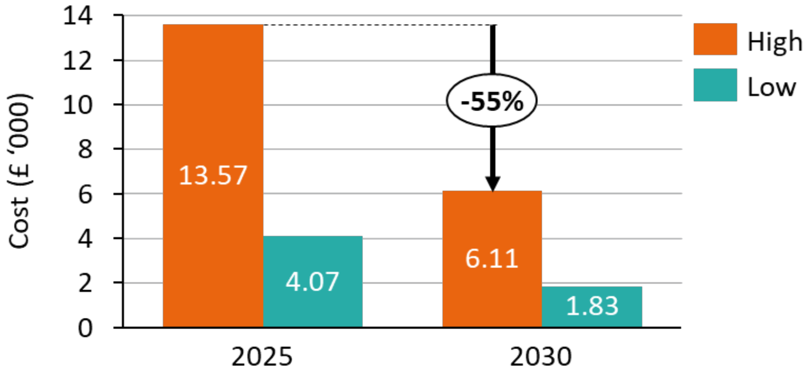

Figure 24: Associated costs (£ 2023) for hardware and installations for a 50 kW AC charger in 2025 and 2030.

Scottish city councils, including Edinburgh and Dundee, are actively exploring the electrification of their RCV fleets. Stakeholder engagement suggests that even if a fleet is open to innovative charging infrastructure and energy system technology, the reliability of the waste collection service remains the highest priority. The primary focus currently lies in electrifying the fleets while ensuring that the operations of the electric vehicles align with the required duty cycles. Exploration of V2G opportunities may be considered for a later stage if a strong use case for participation is established [33], such as through low infrastructure costs and improved revenue opportunities.

While further participation in V2G services could promote the adoption of electric RCVs, the duty cycles of RCVs make them less suitable for V2G.

7 V2G use case modelling

The V2G use case was further investigated for vehicle types with the highest modelled additional value (passenger cars, vans in an urban depot, and trucks in an urban depot). The use case was assessed through cash flow modelling, combining the modelled additional value over smart charging from V2G with the expected costs of the V2G solutions. The additional value from V2G is the value above smart charging. High and low-cost scenarios were developed, considering the uncertainty in future hardware and installation, battery degradation, and maintenance costs. Further detail on the cost scenarios is set out in Appendix 11.5.3.

For each use case, the potential for V2G adoption was modelled assuming the technology was installed in either 2025 or 2030 and assumed a 15-year lifetime of the hardware [12]. Further detail on the uses case modelling assumptions is set out in Appendix 11.5.4.

7.1 Domestic passenger cars

Across both the high and low-cost scenarios, domestic passenger cars see a favourable use case for V2G. As shown in Figure 25, the investment under the high-cost scenario is paid back within 5 years if installed in 2025, and in 2 years if installed in 2030. In the low-cost scenario, the investment is expected to be paid back within one year in both 2025 and 2030.

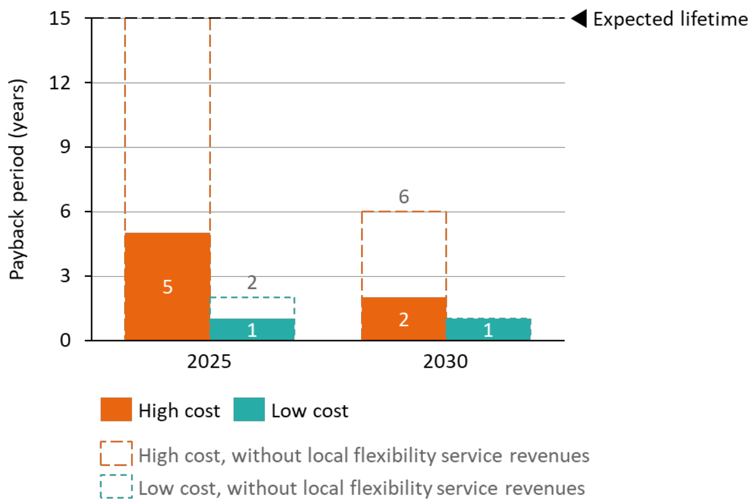

Figure 25: Payback period (years) for domestic passenger cars installing V2G solution in 2025 and 2030 in high and low-cost scenarios, and sensitivity to availability of additional value from local flexibility service.

However, a large proportion of the modelled additional value for passenger cars comes from local flexibility services. Additional value from local flexibility services is location dependent and is therefore only available to customers in Scotland's CMZs. As set out in Section 5.3, Scotland's CMZs present high value services especially in locations where upgrades to the network are expensive, such as in urban locations or extremely remote areas. We investigated the sensitivity to this to understand the use case for V2G without the additional value. These results are set out in Figure 25, and show that the use case is less favourable under the high-cost scenario for customers outside Scotland's CMZs. In such cases, there is no anticipated payback within the assumed 15-year lifetime of the hardware if V2G is installed in 2025, and a 6-year payback if installed in 2030. Conversely, in the low-cost scenario, the additional value from local flexibility services has a lower impact on the use case. A 2-year payback on investment is achieved when V2G is installed in 2025 and 1 year if installed in 2030.

7.1.1 Key findings for passenger cars

- The use case for passenger cars, or for light duty fleets with low daily mileage and with charging windows that span 5.30pm – 8am, is favourable across both high and low-cost scenarios.
- If V2G installation and maintenance costs remain high in the future, installing V2G solutions for domestic passenger cars, even for those in CMZs with access to high additional value from local flexibility services, may not be economically viable until 2025. For those outside CMZs, it will not be cost effective to install V2G solutions until 2030. However, if V2G installation and maintenance costs decrease in the future, V2G adoption could be an effective use case for domestic passenger cars across Scotland from 2025.
- Consumers are highly sensitive to upfront costs [34] and EV uptake related to passenger cars is likely to be limited by supply constraints not consumer willingness, therefore additional value from V2G may not accelerate uptake [35].
- Accelerating the uptake of electric passenger cars can offer significant carbon emissions savings considering that passenger cars are responsible for the largest proportion for Scottish road transport emissions.
- To participate in V2G, customers would need to consider the potential of reduced available energy after charging windows. They will also need to understand the impact of potential battery degradation due to increased cycling.

7.2 Vans in an urban depot

For vans, if V2G installation and maintenance costs are lower in the future, there is a good use case for installing V2G solutions for vans from 2025 onwards. As shown in Figure 26, the investment in V2G is expected to be paid back within 2 years if installed in 2025, and within 1 year if installed in 2030.

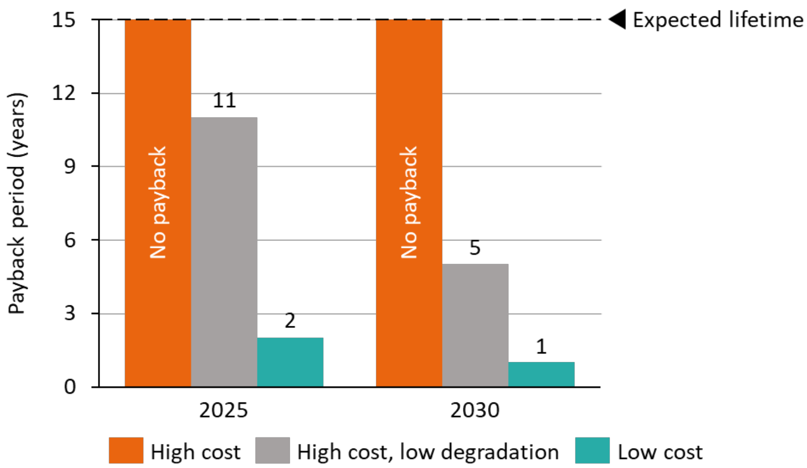

Figure 26: Payback period (years) for vans in an urban depot installing V2G solution in 2025 and 2030 for high and low-cost scenarios, and a sensitivity considering high upfront and ongoing maintenance costs, but low degradation costs.

However, if the V2G installation and maintenance costs are not lower, V2G is not a favourable use case for vans in 2025 or 2030. As shown in Figure 26, there is no payback for the V2G solution within the assumed 15-year hardware lifetime with high costs in either 2025 or 2030. The use case is particularly sensitive to the cost of battery degradation, as vans require high V2G discharge to receive additional value. A sensitivity analysis was applied using hardware and installation and maintenance costs from the high-cost scenario, but battery degradation costs from the low-cost scenario (detail provided in Appendix 11.5.3). As shown in Figure 26, this improves the use case, with installation of a V2G solution in 2025 being paid back within 11 years and installation in 2030 leading to a payback of 5 years.

7.2.1 Key findings for vans

- V2G could be beneficial to vans over 2025 – 2030, if installation and maintenance costs are low or if battery degradation from V2G is minimal.
- The use case for vans, or other light duty fleets with high daily mileage and overnight charging, is improved from 2025-2030 if costs are low or battery degradation is minimal.
- Vans that are returned to drivers' homes instead of depots are more likely to belong to smaller businesses and are likely to benefit from an improved use case for electric vans [36]. However, these customers are also more sensitive to upfront costs [29].
- V2G could accelerate the uptake of electric vans between 2025 and 2030, but operators may need support to cover the increased upfront costs.
- To participate in V2G, customers would need to consider limiting operation to increase available battery capacity. They will also need to understand the impact of potential battery degradation due to increased cycling.

7.3 Trucks in an urban depot

For trucks, in the low-cost scenario, the investment in V2G would be paid back within 4 years if installed in 2025, and 2 years if installed in 2030. However, if costs are high, trucks are unlikely to benefit from V2G. As shown in Figure 27, there is no payback achieved within the assumed 15-year lifetime under the high-cost scenario when V2G solutions are installed in 2025 or 2030.

A sensitivity analysis was carried out to understand the impact of battery degradation on the V2G use case. Sensitivity was assessed using hardware and installation and maintenance costs from the high-cost scenario, but degradation costs from the low-cost scenario (detail provided in Appendix 11.5.3). As shown in Figure 27, this resulted in no payback within the lifetime of the hardware installed in 2025 but led to a 6-year payback period for infrastructure installed in 2030.

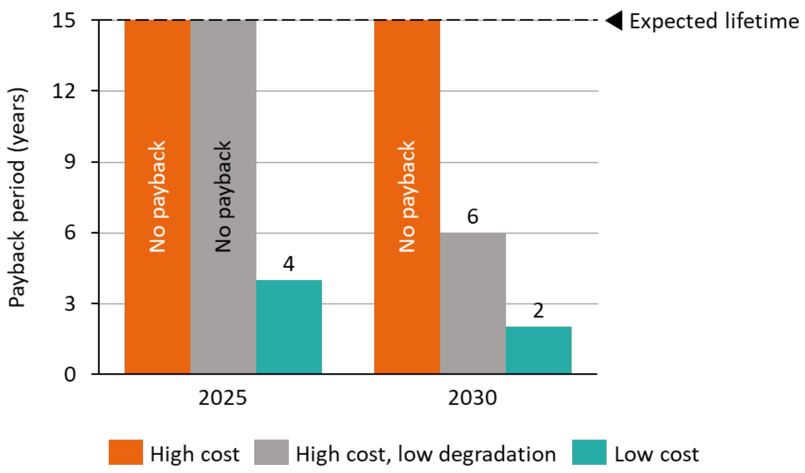

Figure 27: Payback period (years) for trucks in an urban depot installing V2G solution in 2025 and 2030 over high and low-cost scenarios, and sensitivity considering high upfront and ongoing maintenance costs, but low degradation costs.

7.3.1 Key findings for trucks in an urban depot

- Truck fleet operators are expected to benefit from V2G if low-cost hardware becomes available and degradation and maintenance costs are low. However, high upfront investment could be paid back from 2030 if degradation is well managed.
- The use case for rigid urban trucks, or other heavy-duty fleets with moderate mileage and overnight charging, is improved from 2030 if costs are low or battery degradation is minimal.
- Nevertheless, rigid urban trucks are expected to already reach battery electric vehicle total cost of ownership parity with internal combustion engine equivalents between 2020 – 2025 [37]. Consequently, V2G may not significantly accelerate uptake further.
- Trucks with higher mileage and utilisation would struggle to benefit from V2G considering the short charging windows between duty cycles.
- Stakeholder discussions indicate that high upfront costs are a significant barrier to electrification, and V2G would exacerbate this despite the potential value it offers.
- To participate in V2G, customers would need to consider limiting operation to increase available battery capacity. They will also need to assess the impact of potential battery degradation due to increased cycling.

8 Assessment of the potential for V2G to accelerate EV uptake in Scotland

8.1 Conclusions on the use case for V2G in Scotland

We found that investment in V2G solutions could be beneficial for fleets that do not have high daily usage and have long overnight charging windows. However, smart charging without V2G, considered as the baseline taking into account regulations on EV charging infrastructure beyond 2021, can already provide a significant proportion of the value that

V2G can offer. For some vehicle operating cycles, V2G is likely to offer marginal additional benefits over smart charging, especially when accompanied by a significant upfront investment in infrastructure.

Key findings on the V2G use cases included:

1 **The use case for V2G is strongest for vehicles/fleets that exhibit low daily usage and that are charged spanning both peak and low electricity system demand times.**

- Duty cycles of vehicles strongly influence the V2G use case. V2G has higher additional value potential for vehicles with low mileage and electricity consumption, and that are charged both during evening electricity demand spikes and overnight low system demand.
- The potential for V2G is also highest for vehicles that have remaining battery capacity after their daily duty cycles:
    - For instance, passenger cars that have a significant proportion of remaining battery capacity for V2G at the start of their charging window in the evening. These vehicles are therefore able to discharge during the evening when electricity demand and prices are highest, and local flexibility services are most valuable.
    - Fleets with similar charging windows and surplus battery capacity post-duty cycles can benefit from V2G in a similar manner to passenger cars.
- The use case for V2G is not as strong for higher usage vehicles such as vans, buses, RCVs and trucks, which have both higher average daily mileages and electricity consumptions. This limits the available battery capacity for V2G.
- Furthermore, commercial vehicles such as vans, trucks, RCVs and buses face limitations due to the priority of maximising fleet utilisation, which restricts available energy for V2G and the time that EVs can participate in V2G. While V2G could drive EV adoption for commercial fleets through additional revenues, they are likely to prioritise service reliability.

2 **High additional value is available from local flexibility services for vehicles such as passenger cars, but the value is highly location specific and will primarily depend on whether V2G occurs within one of Scotland's CMZs.**

- Our use case modelling showed that passenger cars may be able to participate in local flexibility services within CMZs, which can unlock location specific value. This additional value has a large impact on the use case for adoption of V2G by battery electric passenger cars, or other light duty vehicles with low daily operation and that are charged during the evening peak times. This may therefore accelerate the uptake of EVs.
- Without participation in local flexibility services, the use case for V2G for these vehicles is weakened. Therefore, future V2G business models may target vehicles with an operating cycle within CMZs where local flexibility services are offered by DSOs.
- Current CMZs are situated in grid areas that need flexibility for security of supply; future CMZs are likely to be in zones with high renewable energy generation and/or high electricity demand, although their specific future locations are uncertain.

- Current CMZs identified by SSEN and SPEN are distributed across urban areas including Edinburgh and Dundee, rural regions such as the Highlands and islands including Arran, Lewis and Harris.

3 **The V2G use case is sensitive to infrastructure cost and battery degradation and a positive V2G use case alone may not be sufficient to accelerate EV uptake. Other factors also influence the uptake of EVs, such as upfront costs and supply chain constraints.**

- When compared to smart charging infrastructure, the cost of bidirectional charging infrastructure is a significant barrier to V2G adoption, particularly for upfront-cost-sensitive customers and fleet operators. Fleet operators have reported that the high upfront cost of unidirectional charging infrastructure is a barrier to electrification, and installing V2G infrastructure further increases the upfront investment required.
- The V2G use case additionally depends on managing the cost of battery degradation due to increased cycling of vehicle batteries. These costs must be better understood by consumers and fleet operators before they can commit to V2G business models.
- Lower infrastructure costs and improved understanding of battery degradation costs can improve V2G business models, potentially accelerating the decarbonisation of transport through greater EV adoption.

8.2 Summary of findings

Table 3 presents a summary of the findings for the use cases analysed within this study. It outlines the costs, benefits, opportunities and suitability of V2G for each use case. The quantifiable benefits of V2G are given as annual financial benefits and potential emissions reductions from increased electrification. Additionally, V2G also offers further benefits, such as the potential decarbonisation of the electricity grid through the incorporation of additional renewable generation, which were not included in the scope of this study.

Vehicle type	Upfront V2G costs – High scenario	Upfront V2G costs – Low scenario	Total lifetime costs of V2G – High scenario	Total lifetime costs of V2G – Low scenario	Annual financial benefits	Electrification benefit - Emissions savings ($MtCO_2$)	Specific opportunities for Scotland	Overall suitability of V2G
Passenger cars	£1,900	£570	£5,773	£3,042	£746 per year	4.01 $MtCO_2$	- Participation in CMZs to alleviate grid constraints - Largest decarbonisation potential in terms of emissions and vehicle fleet	Duty cycles are compatible for offering V2G. V2G could offer potential for decarbonising transport but high upfront costs may deter participants.
Vans in an urban depot	£1,900	£570	£7,275	£4,545	£363 per year	1.44 $MtCO_2$	- Participation in CMZs to alleviate grid constraints	Duty cycles are compatible for offering V2G. V2G could offer potential for decarbonising transport but high upfront costs may deter participants.
Trucks in an urban depot	£5,973	£1,792	£21,915	£16,334	£789 per year	1.59 $MtCO_2$	- Participation in CMZs to alleviate grid constraints	V2G could offer additional value but is likely to be a secondary consideration relative to primary business models

Table 3: Showing the summary of the findings. The monetary values are given in £ 2023.

8.3 Recommendations on further research and support

This section outlines recommended areas for further research and support to increase V2G uptake in order to accelerate decarbonisation.

1 **Support is required to remove the high upfront cost barrier to V2G uptake.**
- The high upfront cost of purchasing unidirectional charging infrastructure is a barrier to electrifying certain vehicle types, particularly those that which require high power ratings (trucks, buses and RCVs). The costs are further exacerbated by the extra premium incurred from bidirectional (V2G) hardware.
- Further research and support are necessary to reduce the upfront investment required for V2G solutions, for example through scaling of manufacture and commercial development of lower cost technologies such as bidirectional AC charge points.
- Alternatively, future work could be targeted at providing support incentives to promote investment in V2G infrastructure, although it would be important to ensure that the support targets transport segments that would have high utilisation of V2G.
- Encouraging the development of business models which involve shared bidirectional charging infrastructure would reduce the upfront investment for participating members. Although this could lead to feasibility issues around charger availability, it would add an additional revenue stream for the owners of the V2G chargers.

2 **Improve the ability for EVs to access flexibility value through initiatives such as Balancing Mechanism Wider Access.**
- The use case for V2G is dependent on being able to access value from flexibility services, including the Balancing Mechanism and local flexibility services.
- Currently, some market access rules are pose barriers for distributed assets, despite their technical suitability, or stacking of value streams is prohibited, e.g., with the LCM and DFS.
- Improving access to flexibility markets for customers is a major area of research, and initiatives such as ESO's Balancing Mechanism Wider Access aims to maximise the resources available on the electricity system, while delivering value to energy consumers [38]

3 **Further research is required to improve the understanding of battery degradation from V2G and develop management strategies for minimisation.**
- The effect of battery degradation and the associated cost is a key aspect of the V2G use case. To build an effective use case, vehicle owners and fleet operators will need to understand how V2G affects the battery state of health and the incurred cost from these effects.
- Additionally, minimising battery degradation has a significant impact on the use case for V2G, and therefore effective management will be valuable for the uptake of V2G.

9 References

[1] The Scottish Government, "Policy - Climate Change," 2023. [Online]. Available: https://www.gov.scot/policies/climate-change/reducing-emissions/.

[2] Transport Scotland, "Scottish Transport Statistics, Chapter 13 - Environment," 2022. [Online]. Available: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.transport.gov.scot%2Fmedia%2F53661%2Fchapter-13-environment-reference-tables-scottish-transport-statistics-2022.xlsx&wdOrigin=BROWSELINK.

[3] Climate Change Committee, "Progress in reducing emissions in Scotland 2022 Report to Parliament," Climate Change Committee, 2022.

[4] The Parker Project, "Project final report," 2019.

[5] SSE Energy Solutions, "Bus2Grid Project," 2022.

[6] Nissan, "e4Future & Network Impact V2G projects," 2018.

[7] National Grid ESO, "Powerloop: Trialling Vehicle-to-Grid technology," 2023.

[8] SDG&E, "NewsCenter SDG," 2022. [Online]. Available: https://www.sdgenews.com/article/sdge-and-cajon-valley-union-school-district-flip-switch-regions-first-vehicle-grid-project.

[9] Cenex, "Project Sciurus Trial Insights: Findings from 300 Domestic V2G Units in 2020," 2021.

[10] Guidehouse, "UK Roadmap for Residential Vehicle-to-Grid (V2G)," 2023.

[11] Department for Energy Security and Net Zero, UK, "Regulations: electric vehicle smart charge points," 2023. [Online]. Available: https://www.gov.uk/guidance/regulations-electric-vehicle-smart-charge-points.

[12] ERM, V2Build, UKPN, Wallbox, "Wallbox," 2023.

[13] D. Wang, J. Conignard, T. Zeng and Z. Cong, "Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid services," *Journal of Power Sources,* 2016.

[14] K. Uddin, T. Jackson and et. al., "On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system," *Energy,* vol. 133, 2017.

[15] Transport Scotland, "Scottish transport statistics 2022, Chapter 13 Environment," 2023.

[16] Eunomia, “Ditching Diesel: A Cost-benefit Analysis of Electric Refuse Collection Vehicles,” 2020.

[17] Statista, “Market share of heavy goods vehicles registered in the United Kingdom (UK) in 2021, by region,” 2023. [Online]. Available: https://www.statista.com/statistics/1203278/uk-licensed-hgvs-by-region-market-share/.

[18] Transport Scotland, “Scottish transport statistics 2022, Chapter 1 Road transport vehicles,” 2023.

[19] CXC, “Expanding Scottish energy data – electricity demand,” 2022.

[20] Element Energy, ERM, “Cost and Performance modelling for cars,” 2023.

[21] Element Energy, ERM, *Cost and Performance modelling for vans,* 2023.

[22] CXC, “ULEV Market Segmentation in Scotland,” 2019.

[23] The Welsh Government, “Vehicle Performance Insights: Dennis Eagle eCollect eRCV,” 2023.

[24] Element Energy, “EV Charging Behaviour Study,” 2019.

[25] Daimler Truck; Tennet, “Flexibility marketing options for charging processes of electric medium-duty and heavy-duty commerical vehicles,” 2022.

[26] *ERM analysis of discussion with Scottish fleet operators.* [Interview]. 2023.

[27] Energy Stats UK, “Download Historical Pricing Data,” 2023. [Online]. Available: https://files.energy-stats.uk/csv_output/?_ga=2.241643394.1682293631.1695119043-234045095.1694597090&_gl=1*107l9pl*_ga*MjM0MDQ1MDk1LjE2OTQ1OTcwOTA.*_ga_M45TVRXZ04*MTY5NTExOTA0Mi4zLjAuMTY5NTExOTA0Mi42MC4wLjA.*_ga_Z4Z11HYTZ1*MTY5NTExOTA0My4zLjAuMTY5NTExOTA0.

[28] UKPN, “UK Power Networks,” 2022. [Online]. Available: https://ukpowernetworks.opendatasoft.com/explore/dataset/optimise-prime/information/.

[29] Element Energy, ERM for the Climate Change Committee, “Analysis to identify the EV charging requirement for vans,” 2022.

[30] Transport Scotland, “Scottish Transport Statistics 2022 - Chapter 11 Personal and Crossmodal,” 2023. [Online]. Available: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.transport.gov.scot%2Fmedia%2F53058%2Fchapter-11-personal-and-crossmodal-reference-tables-scottish-transport-statistics-2022.xls&wdOrigin=BROWSELINK.

[31] Statista, 2023. [Online]. Available: https://www.statista.com/statistics/320205/refuse-disposal-licensed-commercial-

vehicles-by-weight-in-the-united-kingdom/#:~:text=In%202021%2C%20the%20number%20of,around%2017%2C800%20units%20in%202021.

[32] Stakeholder engagement with a Scottish City Council, 2023.

[33] ERM analysis of discussion with a Scottish City Council, 2023.

[34] Element Energy, ERM, “Electric Mobility: Inevitable, or Not? A report for the Platform for Electromobility,” 2022.

[35] ERM, “ERM consumer choice modelling compared with supply constraint data from IHS,” 2023.

[36] Element Energy, ERM, “Analysis to identify the EV charging requirement for vans,” 2022.

[37] Element Energy, “Battery electric HGV adoption in the UK: barriers and opportunities,” 2022.

[38] National Grid ESO, “Balancing Mechanism Wider Access,” [Online]. Available: https://www.nationalgrideso.com/industry-information/balancing-services/balancing-mechanism-wider-access.

[39] Cenex, “Commercial Viability of V2G: Project Sciurus White Paper,” 2021.

[40] Cenex, “EV-elocity - Project Final Report,” 2022.

[41] Nissan Motor GB, “THE DRIVE TOWARDS A LOW-CARBON GRID I Unlocking the value of vehicle-to-grid fleets in Great Britain,” 2021.

[42] Connected-Energy, “Powering the charge ahead,” 2023.

[43] Energy saving trust, “Powerloop Vehicle-to-Grid trial,” 2023.

[44] Transport Studies Unit, University of Oxford, “Advantages of Electric Vehicle adoption and Vehicle-to-Grid charging in the fleet market: Lessons from the V2GO project,” 2020.

[45] UKPN, Hitachi, “Optimise Prime - Final Learning Report,” 2023.

[46] Nick Banks, “Vehicle to Grid (V2G) Barriers and Opportunities a capability approach,” 2021.

[47] DTU, Nuuve, Nissan, “The Parker Project - Final Report,” 2019.

[48] Hitachi, “JumpSmartMaui,” 2013. [Online]. Available: https://www.pecc.org/resources/minerals-a-energy/2162-island-smart-grip-project-on-maui-jumpsmartmaui/file.

[49] Novatlantis, “Pioneering trial involving bidirectional electric vehicle charging,” 2022.

[50] Council of the Isles of Scilly, “Council launches electric vehicle project on Scilly as part of the Smart Islands programme,” 2019. [Online]. Available: https://www.scilly.gov.uk/news/council-launches-electric-vehicle-project-scilly-part-smart-islands-programme.

[51] Aug.e, 2023. [Online]. Available: https://www.aug-e.io/en/case/deeldezon/.

[52] J. van der Hoogt, E. van Bergen and J. Warmerdam, “SEEV4-City: KPI Results - Baselines and Final Results,” 2020.

[53] European Commissison, “Construction : Report on EVVE first deployment,” 2021.

[54] E-flex, “CO2 savings in Greenwich with V2G vehicles,” 2021. [Online]. Available: https://www.e-flex.co.uk/blog/2021/3/15/co2-savings-in-greenwich-with-v2g-vehicles.

[55] Uve, “www.uve.pt,” 2022. [Online]. Available: https://www.uve.pt/page/v2g-azores-tecnologia-inovadora-em-acao-nos-acores/.

[56] European Commission, “DrossOne V2G Parking: Large-scale vehicle-to-grid system with integrated stationary storage,” 2021.

[57] Leiva, Javier; UIA Expert , “AirQon Final Journal,” 2023.

[58] E. Zafeiratou and C. Spataru, “Modelling electric vehicles uptake on the Greek islands,” *Renewable and Sustainable Energy Transition,* 2022.

[59] California Energy Commission, “Distribution System Constrained Vehicle-to-Grid Services for Improved Grid Stability and Reliability,” 2019.

[60] Frontier Group, “Electric School Buses and the Grid - Unlocking the power of school transportation to build resilience and a clean energy future,” 2022.

[61] N. Manthey, “Electrive,” 2023. [Online]. Available: https://www.electrive.com/2023/03/21/nottingham-now-home-to-one-of-uks-largest-v2g-installation/.

[62] SSE, “SSE Energy Solutions,” 2023. [Online].

[63] Transport Scotland, “Scottish Transport Statistics 2022,” 2022. [Online]. Available: https://www.transport.gov.scot/publication/scottish-transport-statistics-2022/chapter-01-road-transport-vehicles/.

[64] Transport Scotland, “Scottish Transport Statistics 2022,” 2023.

[65] Scottish Government, “Urban-Rural Classification Mid Year Population Estimates,” 2020. [Online]. Available: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.gov.scot%2Fbinaries%2Fcontent%2Fdocuments%2Fgovscot%2Fpublications%2Fadvice-and-

guidance%2F2022%2F05%2Fscottish-government-urban-rural-classification-2020%2Fdocuments%2Fscottish-governmen.

[66] Octopus Energy, “Introducing Agile Octopus,” 2018. [Online]. Available: https://octopus.energy/blog/outgoing-faqs/.

[67] National Grid ESO, “Local Constraint Market (LCM) - Product & Service Design,” 2022.

[68] National Grid ESO, “Monthly Balancing Services Summary, March 2023,” 2023. [Online]. Available: https://www.nationalgrideso.com/data-portal/mbss#:~:text=The%20Monthly%20Balancing%20Services%20Summary,as%20by%20each%20individual%20service..

[69] Flexible Power, “www.flexiblepower.co.uk,” 2023. [Online]. Available: https://www.flexiblepower.co.uk/locations/sp-energy-networks/sp-energy-networks/where-we-are-procuring-flexibility.

[70] National Grid ESO, “Future Energy Scenarios,” 2023.

[71] European Commission, “Innovation Fund Programme - Overview of awarded projects in Italy,” 2022.

[72] Sono Motors, “Sono Motors,” 2021. [Online]. Available: https://sonomotors.com/en/blog/were-developing-a-bidirectional-wallbox-how-it-looks-is-up-to-you/.

[73] ERM discussion Depot Charge Point Operators, [Online].

[74] Element Energy, “V2GB Vehicle to Grid Britian,” 2019.

[75] The Australian National University, “The A to Z of V2G,” REVS, 2021.

[76] The Australian National University, “Modelling V2G: A study on the economic and technical value proposition for V2G,” REVS, 2022.

[77] D. Huber, “Vehicle to Grid Impacts on the Total Cost of Ownership for Electric Vehicle Drivers,” *World Electric Vehicles Journal,* 2021.

[78] Geotab, “What 6,000 EV batteries tell us about EV battery health,” 2020. [Online]. Available: https://www.geotab.com/blog/ev-battery-health/.

[79] Thingvad, A., et. al., “Empirical Capacity Measurements of Electric Vehicles Subject to Battery Degradation From V2G Services,” *IEEE Transactions on Vehicular Technology,* vol. 70, no. 8, 2021.

[80] BNEF, “BNEF Global EV Outlook 2023,” 2023.

[81] V2GHub, “www.v2g-hub.com,” 2023. [Online]. Available: https://www.v2g-hub.com/insights.

[82] Everoze, EVConsult, “V2G GLOBAL ROADTRIP: AROUND THE WORLD IN 50 PROJECTS,” 2018.

[83] Executive Director of City Development, Dundee City Council, “SUPPLY OF ZERO EMISSION VEHICLES,” 2021.

[84] Scottish Government, “Energy Statistics for Scotland - Q1 2023,” 2023. [Online]. Available: https://www.gov.scot/publications/energy-statistics-for-scotland-q1-2023/pages/grid-emissions/.

[85] EVBOX, “ww.evbox.com,” 2021. [Online]. Available: https://evbox.com/uk-en/how-much-electricity-does-an-electric-car-use#:~:text=The%20UK%20Department%20of%20Transport,and%201%2C296%20kWh%20per%20year..

[86] The Scottish Government, EY, “Low Carbon Investment - Scottish Bus Electrification commercial and economic content,” 2020.

[87] “Renewables Ninja,” 2023. [Online]. Available: https://www.renewables.ninja/.

[88] ERM, *Modelling of electric HGV performance,* 2023.

[89] *ERM analysis of discussion with fleet operators.* [Interview]. 2023.

[90] Transport Scotland, “STAG technical database,” 2018.

[91] The Scottish Government , “Percentage Population Estimates by Urban Rural Classification,” 2020. [Online]. Available: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.gov.scot%2Fbinaries%2Fcontent%2Fdocuments%2Fgovscot%2Fpublications%2Fadvice-and-guidance%2F2022%2F05%2Fscottish-government-urban-rural-classification-2020%2Fdocuments%2Fscottish-governmen.

[92] Transport Scotland, “Scottish Transport Statistics,” 2023. [Online]. Available: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.transport.gov.scot%2Fmedia%2F53038%2Fchapter-1-road-transport-vehicles-reference-tables-scottish-transport-statistics-2022.xlsx&wdOrigin=BROWSELINK.

[93] K. Uddin, T. Jackson, W. Widanalage, P. Jennings and J. Marco, “On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system,” *Energy,* 2017.

[94] Major bus fleet operator in the UK, 2023.

[95] UK Power Networks, “UK Power Networks,” 2022. [Online]. Available: https://ukpowernetworks.opendatasoft.com/explore/dataset/optimise-prime/information/.

[96] V2GO, 2021.

[97] Stakeholder engagement with major truck fleet operator , 2023.

[98] SSEN, “Flexibility Services Procurement,” 2023. [Online]. Available: https://www.ssen.co.uk/our-services/flexible-solutions/flexibility-services/flexibility-services-procurement/.

[99] ERM, *Analysis based on discussion with vehicle manufacturers.*

[100] *ERM analysis of discussion with bus fleet operator.* [Interview]. 2023.

[101] T. Scotland, “STAG Technical Database,” 2018. [Online]. Available: https://www.transport.gov.scot/publication/stag-technical-database/section-9/#s944.

[102] ERM, *Analysis of discussion with depot managers,* 2022.

[103] ERM, “The future of the bus vehicle market in Scotland,” ClimateXChange Publications, Edinburgh, 2022.

[104] National Grid ESO, “Dynamic Containment: what is it, and why do we need it?,” 2023. [Online]. Available: https://www.nationalgrideso.com/news/dynamic-containment-what-it-and-why-do-we-need-it.

10 Appendix: Further detailed analysis

10.1 Identified V2G trials

The literature review resulted in 23 identified projects that explored V2G across various vehicle types and locations. The trials were primarily concentrated in the UK and other parts of Europe, including Denmark, Belgium, France, Switzerland, Italy, Greece, and Germany. As shown in Figure 28, the identified trials were mainly located in public charge points or depots, although some at home or work locations were found. The trials involved mainly passenger cars (64%) but light goods vehicles (LGVs) and heavy goods vehicles (HGVs) also featured. Most trials were categorised as commercial with less than a third covering domestic transport.

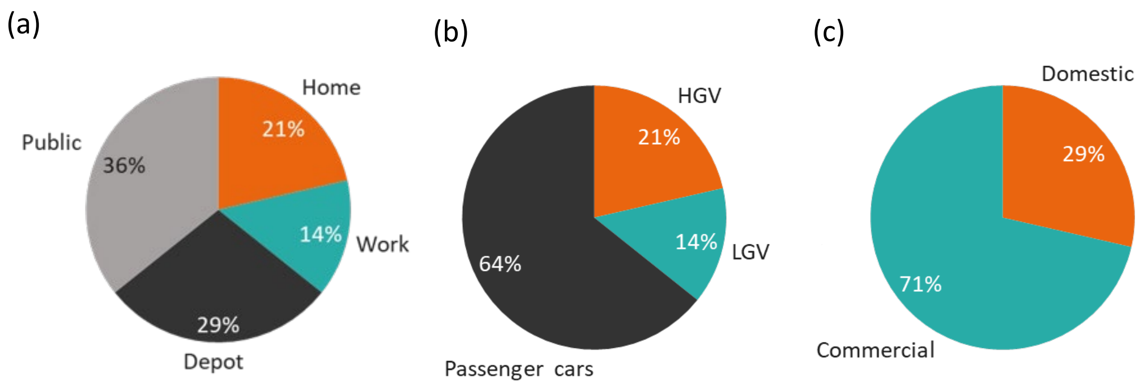

Figure 28: Summary statistics of identified V2G trials including (a) location of trial; (b) vehicle type; and (c) categorisation of trial.

The trial name, description and source are given in Table 4. Deep dives on four key examples of trials are described in Appendix 10.1.1.

V2G trial name	Brief description	Source
Project Sciurus	Commuter passenger cars doing V2G at home for energy bill savings from the wholesale electricity market	[39]
Bus2Grid	Proof of concept trial using V2G with buses in an urban depot	[5]
EV-elocity	Commuter EVs in work carparks doing energy arbitrage and load shifting	[40]
E4Future	Passenger cars being used to support renewable energy penetration	[41]
CleanMobil Energy	HGVs coupled with solar PV and storage to avoid peak tariffs during charging	[42]
Powerloop	Passenger cars using V2G at home to provide flexibility services	[43]
V2GO	Commercial LGV fleets using V2G for offering flexibility services	[44]
Optimise Prime	Commercial LGV fleets using V2G for offering flexibility services	[45]
Project LEO	Commuter EVs at office car parks for energy arbitrage and flexibility services	[46]

Parker	Passenger cars at public car parks using V2G for offering flexibility services	[47]
JumpSmartMaui	Passenger cars using V2G to store excess renewable generation on the system	[48]
V2XSuisse	Shared passenger cars and vans at commercial EV carparks offering additional capacity to minimise grid upgrades	[49]
Scilly	Shared passenger cars at commercial carparks to maximise self-consumption of on-site renewables	[50]
Deeldezon	Domestic passenger cars to maximise self-consumption of on-site solar PV	[51]
SEE4-City	Passenger cars at a stadium car park offering peak shaving	[52]
EVVE	Shared EVs at work carparks doing energy arbitrage	[53]
E-Flex	City depot HGVs charging during high renewable generation and discharging into the grid when required	[54]
V2G Azores	Passenger cars employ V2G at home and work carparks for tariff savings and grid integration with renewables	[55]
DrossOne	Commuter EVs at office car parks for energy arbitrage and flexibility services	[56]
AirQon	Shared company cars used to provide power in times of peak demand at a festival event	[57]
Hellenic Islands Study	Modelled benefits of V2G to improve integration of solar PV	[58]
Electric Power Research Institute Project	Passenger cars used within an end-to-end system implementation and demonstration of vehicle-to-grid capable vehicles	[59]
Electric School Buses USA Projects	Electric school buses doing V2G to unlock benefits for local DNOs and fleet operators.	[60]

Table 4: The findings from the literature review including V2G trial name, a brief description of the trial and relevant source.

10.1.1 Deep dives on key trials

Deep dives on four key examples of trials are shown below, to illustrate the information collected and the variety of projects considered. The deep dives include JumpSmartMaui [48], Nottingham City Council [61], Project Sciurus [39] and Bus2Grid [62].

JumpSmartMaui

Summary:
Passenger cars were used for V2G to store excess renewable energy and provide flexibility services to the DNO in Maui.

Trial information:

- Hitachi supplied 200 passenger cars to volunteers.
- 80 chargers were installed in rural households and urban public carparks across the island.

Benefits identified:

- EV charging times were shifted to align with excess electricity from renewables.
- V2G was used to discharge into the grid during hours of peak demand.

Nottingham City Council

Summary:
This project uses V2G enabled refuse collection vehicles (RCVs) to offer flexibility services and maximise consumption of on-site renewables.

Trial information:

- Nottingham City Council and Connected Energy have installed 40 V2G chargers in an urban depot containing 250 EVs including 6 electric RCVs.
- The trial aims to decarbonise operations of the depot using EVs coupled with V2G and on-site PV generation.

Benefits identified:

- The ongoing project aims to use the electric fleet and V2G to isolate the depot during peak demand and avoid peak tariffs.

Project Sciurus

Summary:
This project utilised passenger cars and V2G to demonstrate that V2G technology works at a residential level.

Trial information:

- 320 V2G units were installed in real homes across the UK.
- Kaluza developed a platform for optimal charging and discharging times based on the customer needs.

Benefits identified:

- EV charging times were shifted from peak demand to when the grid would have excess supply from RES.
- V2G was used to discharge into the grid during peak demand hours.

Bus2Grid

Summary:
This project used electric buses and V2G to offer aggregated capacity in a depot in London.

Trial information:

- Go-Ahead, London's largest bus company, operates 28 BYD/ADL Enviro 400EVs at the UK's largest electric bus depot.
- Exploring V2G for commercial benefits, including frequency response and energy arbitrage.

Benefits identified:

- Project was the first demonstration of V2G from e-buses, demonstrating >1 MW of aggregated capacity.
- V2G was used to discharge into the grid during peak demand hours.

10.2 Development of V2G opportunities

V2G opportunities identified from the trials identified from the literature included vehicle type, geographical context, charging window and local environment, as shown in Table 5.

Categories	Description
Situation	Including vehicle type and geographic context.
Charging window	The hours during the day when the EV is charging, therefore when V2G can occur
Local environment	The location where the EV is being charged and where V2G can occur such as at home, public car park or at a depot

Table 5: Descriptions of the key categories used to define the different opportunities for V2G.

We identified twelve distinct V2G opportunities for further assessment. The list of V2G opportunities, including a high-level description of the charging window and local environment, is presented in Table 6. In this study, the term 'trucks' refers to urban rigid heavy goods vehicles, which we assume as typically used for last mile distribution to stores (typically 18t or 26t rigids).

Vehicle type	Charging window	Local environment
Urban passenger cars	**Overnight** (5:30am – 8am)	Private off-street parking
Urban commuter passenger cars	**Daytime** (8:30am-5pm)	Private work car park with on-site renewables
Rural passenger cars	**Overnight** (5:30am – 8am)	Private and public car parks
Urban passenger cars	**Evening** (Variable)	Event space car park
Urban passenger cars	**Overnight** (5:30am – 8am)	Public car park
Rural shared passenger cars	**Overnight** (5:30am – 8am)	Public car park on an island
Urban buses	**Overnight** (12pm-6am)	Depot with on-site renewables
Rural buses	**Overnight** (12am – 5am)	Depot with on-site renewables
Urban vans	**Overnight** (7pm – 8:30am)	Depot with on-site renewables
Shared urban vans	**Overnight** (7pm – 8:30am)	Public and private car parks
Urban RCVs	**Overnight** (3:30pm – 7am)	Depot with on-site renewables
Urban trucks	**Overnight** (5pm – 5am)	Depot with on-site renewables

Table 6: List of the V2G opportunities categorised by charging window, local environment and associated relevant trial.

10.2.1 Assessment of opportunities

Financial savings and other benefits identified in the literature were used to categorise each V2G opportunity as either a high, medium, or low benefit. Benefits include financial savings from grid services, energy arbitrage (described in Section 10.3.1), and integration of on-site renewables. Additionally, other benefits such as the reduction of curtailment from local renewables, avoiding the use of high carbon technologies, and peak demand reduction were used in the categorisation. Further details on the financial savings and other benefits from V2G are given in Appendix 10.3.

We assessed the V2G opportunities in the context of the Scottish fleet's size and respective emissions. We ranked the opportunities to highlight the potential decarbonisation potential from V2G. Figure 29 shows a breakdown of Scottish road transport emissions in 2021, with passenger cars accounting for the majority of vehicle emissions in Scotland at 53.3%, followed by HGVs at 20.6%, LGVs at 20.2%, buses and coaches at 1.2%. Furthermore, in 2021 Scottish road transport fleet was mostly comprised of passenger cars (84.5%) with LGVs at 10.6%, HGVs at 1.2% as shown in Figure 29.

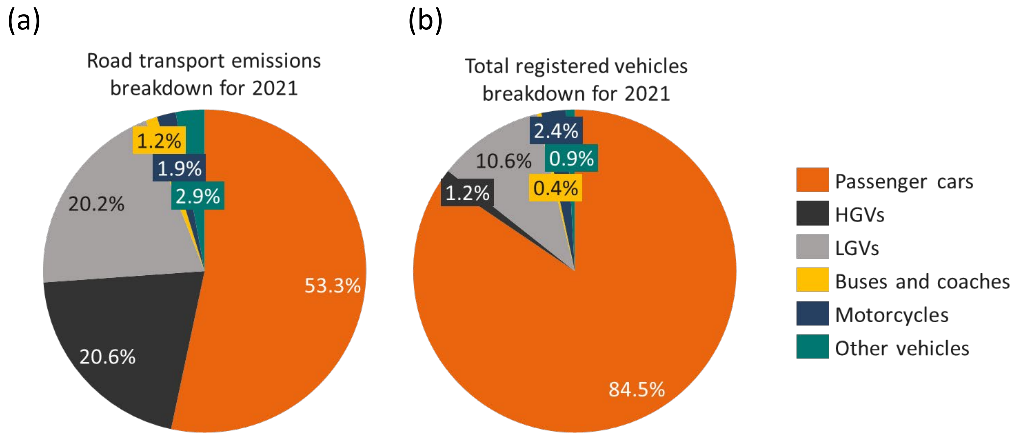

Figure 29: (a) 2021 road transport emissions [2]. (b) 2021 total registered vehicles [63].

Furthermore, most vehicles across all vehicle types are operated in an urban local environment, particularly passenger cars and buses (Figure 30).

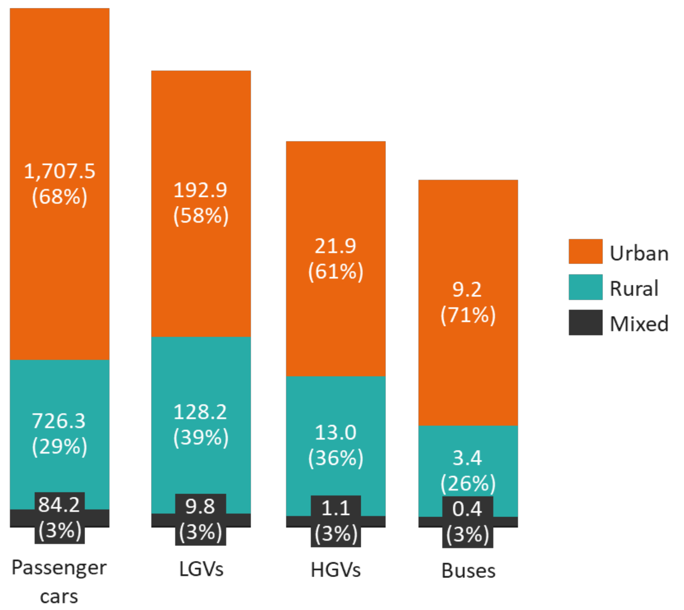

Figure 30: Breakdown of registered vehicles split by urban, rural, and mixed environments. Urban, rural and mixed classifications were allocated based on the number of registered vehicles within a given council [64] and the urban-rural population split for each council [65]. [8]

10.3 Financial benefits

V2G can create financial savings for customers through participation in flexibility services, energy arbitrage, and minimising grid electricity consumption through the utilisation of on-site renewable generation.

From the research on V2G trials outlined in Section 10.2 there is a significant emphasis placed on Frequency Response, which is made up of several products including Dynamic Containment, as a key V2G benefit. However this neglects considerations of technical and metering barriers in products like Dynamic Containment. The most significant V2G advantages will likely come from the combination of services, such as energy arbitrage with integration of on-site renewable energy sources.

10.3.1 Energy arbitrage

Energy arbitrage generates financial value by capitalising on fluctuations in energy prices. V2G can be used to sell electricity (discharge) back to the grid during periods of high prices and to buy electricity (charge) when prices are lower. Energy markets operate on a national (Great Britain) level, meaning that there isn't a distinct market solely for Scotland. Energy trading is conducted by suppliers, who can pass on the benefits to consumers through tariffs, including export tariffs and time-of-use tariffs. A current example of this is the 'Agile Octopus' offered by Octopus energy [66]. This pricing mechanism changes every half hour based on wholesale electricity processes and aims to reduce demand when electricity prices are high.

[8] "Urban" councils have over 50% of their population in "large urban" or "other urban" locations, "Rural" councils have over 50% outside "large urban" or "other urban" locations, and "Mixed" councils have almost equal splits in both urban and rural locations.

10.3.2 Flexibility services

V2G can also generate financial value by participating in flexibility services which provide system benefits, such as frequency response and constraint management. In Scotland, flexibility services are particularly focused on the constraints in the transmission network at the Scotland-England border [67]. Scotland's high renewable potential can exceed the network capacity, resulting in constraint costs caused by curtailment. In FY23, this cost amounted to £344 million, representing 8% of the total expenses required to operate the network and one of National Grid ESO's (ESO) greatest expenditures in the year [68]. The ESO has two key tools to mitigate the need to curtail renewable generation in Scotland:

1. The Balancing Mechanism is the primary tool for addressing constraints on the Scotland-England border. Assets are dispatched in real-time to adjust demand or generation, thereby maximising the penetration of Scottish renewables. This presents an opportunity for Scottish V2G, as many customers could be paid to charge or discharge their EVs.
2. The Local Constraint Market is a new ESO market currently being trialled to help manage network constraints at the Scotland-England border. The service aims to involve domestic and commercial consumers in constraint management, offering a demand turn-up service for those unable to access the Balancing Mechanism. This is based on stringent metering requirements of the Balancing Mechanism which are not fulfilled by most domestic charge points. It is important to note that participation in this service cannot be stacked with other services, as it serves as an "entry level" flexibility product.

10.3.3 Constraint Managed Zones

Additionally, both Scottish distribution network operators, Scottish & Southern Electricity Networks and Scottish Power Energy Networks oversee a number of Constraint Managed Zones, where they procure local flexibility services to alleviate or defer network upgrades, as shown in Figure 31. These zones are distributed across urban areas like Edinburgh and Dundee, rural regions such as the Highlands, and islands including Arran, Lewis, and Harris. V2G can provide these services by discharging energy into the local grid when dispatched by SSEN or SPEN. As the adoption of electric heating and electric vehicles accelerates in Scotland, the need for CMZs is expected to grow, and their financial value can be particularly high in areas where network upgrades are costly, such as urban or remote locations.

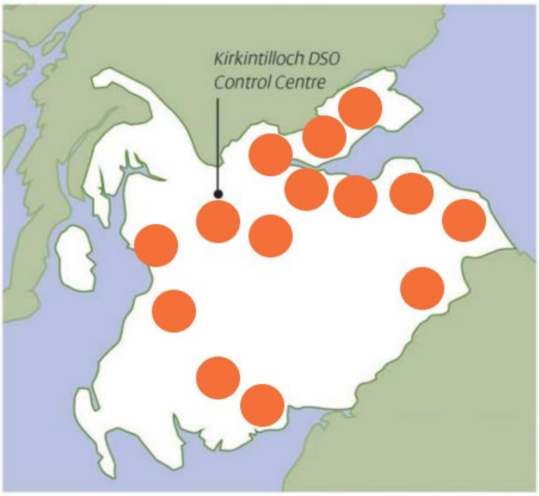

Figure 31: Illustrative mapping of Constraint Managed Zones for SPEN [69]. The orange circles indicate the locations of the CMZs within the network operated under SPEN – note: locations are illustrative and do not show precise areas.

10.3.4 System benefits

V2G technology could be used to relieve grid congestion during periods of high renewable energy production and at times of peak demand from consumers. This reduces carbon emissions by avoiding the utilisation of high-carbon technologies such as gas power plants for grid balancing, as described in Table 7.

System benefit	Description
Reducing curtailment from local renewables	EVs can charge during high renewable generation, preventing curtailment of renewable generation and storing for discharge during low renewable generation.
Reducing use of high carbon technologies	Flexibility services such as frequency response (described in 10.3.2) can be provided by V2G EVs instead of gas- or diesel-powered generators.
Peak demand reduction	EVs can lower electricity consumption during times of peak demand on the electricity grid. This lowers the risk of congestion on the grid, and the need to carry out costly grid upgrade to ensure grid can deliver the demand required..

Table 7: Description of the various system benefits that V2G can offer.

The ESO anticipates that V2G will play a significant role in providing power system flexibility, although this transformation may not be fully realised until after 2030 [70]. The delay is primarily attributed to the time it takes for the benefits of V2G to outweigh the system costs. Table 8 outlines the projected increases in system peak demand in Scotland from 2025 to 2050. V2G is projected to reduce the system's peak demand by 1% in 2030, reaching 12% reduction by 2050 from increased uptake of EVs. Figure 32 shows the system peak reduction in terms of GW from 2025 to 2030, which levels off at 1.4 GW beyond 2040.

Year	2025	2030	2035	2040	2045	2050
System peak in Scotland (GW)	4.7	5.9	8.0	10.2	11.4	11.4
Percentage of peak reduced by V2G	0%	1%	7%	14%	12%	12%

Table 8: The projected peak electricity demand in Scotland from 2025 to 2050 and the percentage of peak demand reduced by V2G [70].

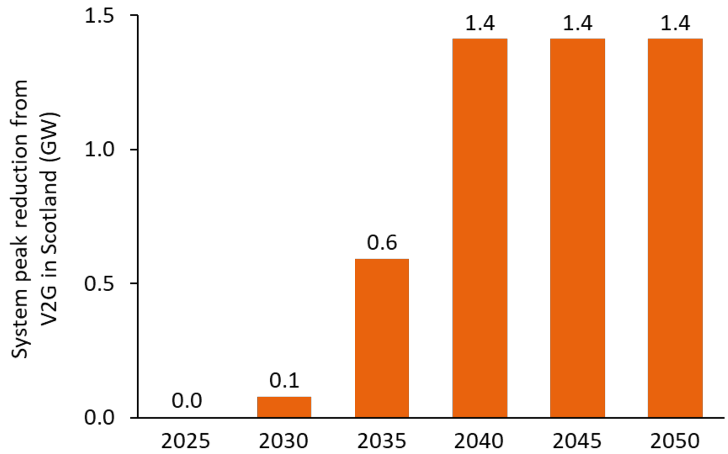

Figure 32: The potential for V2G to reduce peak electricity demand in Scotland in terms of system peak reduction from 2025-2050.

10.3.5 Carbon benefits

V2G can lower grid carbon emissions by reducing curtailment and use of high carbon technologies for flexibility services or at times of peak demand. For instance, a study conducted in the UK in 2021 [41] estimated that the introduction of 50,000 V2G-enabled electric vehicles between 2025 and 2030 could reduce annual CO_2 emissions by approximately 60 tCO_2e per year in the UK, primarily by preventing the curtailment of renewable output, especially wind generation. Further carbon emissions savings have been identified in the literature, notably 63 $ktCO_2e$ of expected annual emissions avoided in the UK from the utilisation of approximately 30 MW of V2G capacity [71]. These carbon emissions savings are expected through the utilisation of EVs to provide fast response to deliver grid services, reducing the use of carbon-intensive gas plants.

10.4 Review of costs associated with V2G

V2G requires additional hardware and power electronics to enable the bidirectional flow of electricity between the EV battery and the grid, for both alternating current (AC) and direct current (DC) technologies. Presently, DC V2G chargers are significantly more expensive than smart chargers, but costs are expected to decrease with increased manufacturing volumes and technological advancements. AC V2G is expected to be lower cost than DC but still more expensive than smart chargers [72]. Although maintenance cost is typically low for all chargers, it may rise to approximately £100 per year per charger (£ 2023) for general repairs for more complex V2G hardware [73]. Also, although it is uncertain (and discussed in more detail in Section 10.4.2, we expect V2G to lead to more rapid battery degradation [13]. This may incur ongoing costs, even if covered by car warranties. These cost factors influence the viability of V2G use cases and explored further in the following sections.

10.4.1 Hardware and installation

The high costs associated with DC bidirectional chargers stem from the need for both a DC charger and a grid-tied inverter. Both components use power electronics similar to those used in solar PV inverters. Previous analysis used projected costs of PV inverters to project the falling price premium of DC V2G chargers, modelling a 67% fall in price between 2023 and 2030 [74].

Although AC V2G is currently in trial stages and the precise cost of its hardware remains uncertain, AC bidirectional chargers are anticipated to be significantly less expensive than DC. AC V2G hardware manufacturers, such as Sono Motors [72], estimated that the hardware premium for AC bidirectional chargers would be approximately 70% lower than that of DC bidirectional chargers, which can be estimated as an additional cost (premium) of £948 in 2023 [72]. Nevertheless, the costs for installing an AC V2G charger are expected to remain more costly than those for a standard AC smart charger, primarily due to the more intricate controlled rectifiers required to facilitate bidirectional power flow [75].

The cost reduction projections [74] were updated considering the 2023 estimation of the cost premium for DC and AC chargers, with “premium” meaning the additional cost beyond that of a smart charger (Figure 33). The high and low cost scenarios are explained in Section 11.5.3.

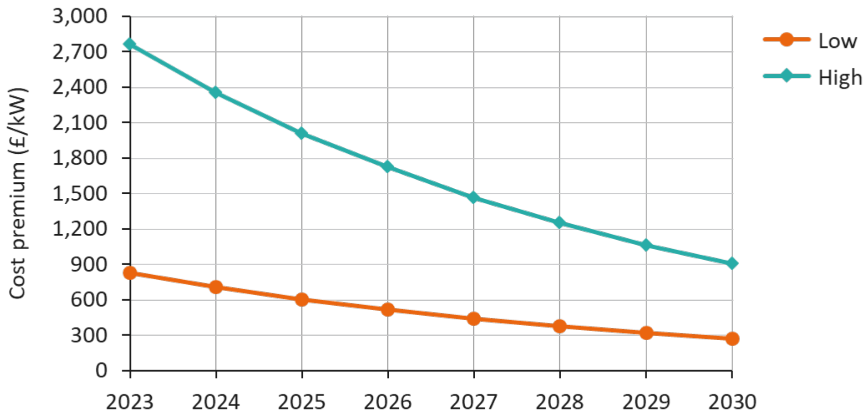

Figure 33: Cost premium (£ 2023) of a V2G charger above that of a 7.2 kW unidirectional smart charger, for both a low and high scenario. These scenarios are calculated from available data in the literature [74, 76, 72].

Literature has suggested that the costs roughly scale with the rated power of the charger [74, 77, 75], although the relationship may not be perfectly linear [75]. These considerations highlight the complexities of V2G charger costs.

10.4.2 Battery degradation

A comprehensive literature review on battery degradation in EVs was conducted, using recently published research and real-world data.

There are two forms of battery degradation to consider:

- Cycling degradation: battery capacity gradually diminishes with each charge/discharge cycle, signifying that the more cycles a battery undergoes, the greater its degradation [13].
- Calendar degradation: battery capacity can fade over time, particularly when the battery is left at extreme states of charge (0% or 100% SOC) [14].

Real-world data obtained from Geotab suggests that EV batteries degrade by approximately 0.04% of their state of health per discharge cycle [78]. However, this discharge rate includes both cycling and calendar degradation. Further research has been conducted with the aim of distinguishing the effects of cycling and calendar degradation on battery state of health. Research from the Technical University of Denmark suggests that cycling degradation alone leads to approximately 0.005% state of health (SOH) reduction per discharge cycle [79].

Two scenarios were modelled to represent the cost of increased battery degradation as a result of V2G, expressed as a cost per MWh discharge. The high scenario is based on the Geotab data [78] and the low scenario assumes that increased degradation from V2G is solely from cycling degradation [79]. The modelling is shown in Figure 34, and indicates the high uncertainty (77%) in the impact of battery degradation on the V2G use case.

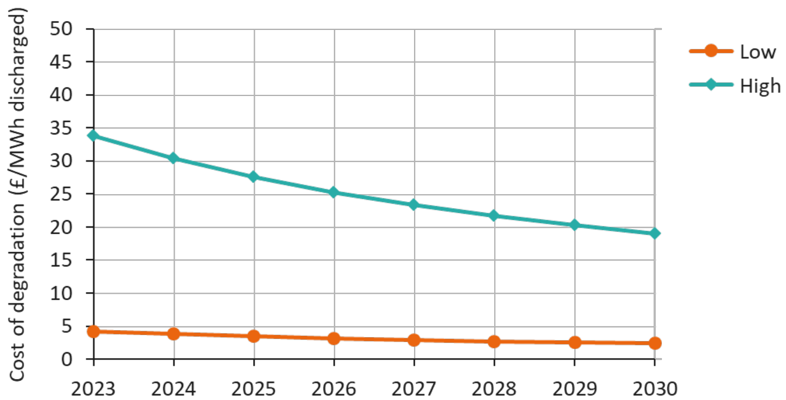

Figure 34: Cost of battery degradation (£ 2023) due to V2G used in modelling for low and high scenarios. To calculate these scenarios, two degradation rates were found in the literature [79, 78] and applied to Bloomberg battery pack cost projections [80].

10.5 Stakeholder engagement

The project included three stakeholder engagement sessions related to the identified use cases. The stakeholder engagement sessions involved discussion of key topics, including:

- Typical duty cycles of the fleet
- Electric models within the fleet, past or planned electrification experience and electric charging infrastructure
- Opportunities and barriers to V2G, including any past experience

The list of stakeholders and relevant vehicle types discussed during the session are given in Table 9.

Stakeholder	Vehicle type
Dundee City Council	Refuse collection vehicles
Menzies Distribution	Vans and trucks
Go-Ahead London	Buses

Table 9: Showing stakeholder engagement details including the organisation and the vehicle types discussed.

11 Appendix: Detailed modelling method

11.1 Key data sources

Key data sources have been included in Table 10. These were used as a basis to begin the literature review process.

Data sources reviewed	Relevance to the project	Source
V2G Hub	Information on V2G trials around the world was provided in a dataset. The dataset included key information regarding the trials including location, timeline, the number of V2G chargers, grid services and status of service provided.	[81]
V2G Global Roadtrip: Around the World in 50 Projects	This report provided a global review of V2G projects, teasing out lessons learned for the UK and beyond.	[82]

Table 10: Data sources for the literature review process.

11.2 Method breakdown

The project was separated into 5 tasks which are described in Table 11. The first two tasks involved a literature review to understand the current V2G market, looking at findings from V2G trials and associated costs from V2G. From this process, opportunities for V2G were identified and ranked according to their impact. Task 4 explored the additional value for V2G with respect to use cases chosen from the list of opportunities. Finally, Task 5 involved the generation of this report providing the assessment of the potential for V2G to accelerate the decarbonisation of road transport in Scotland.

Task	Description
1	Identification of 10-15 opportunities for V2G with potential to provide carbon benefits to Scotland's transport system, categorised by transport sector, vehicle type, local environment, and geographic context.
2	Aggregation of cost data and values of potential benefits of V2G technology.
3	Development of 5 use cases, including archetypal vehicle type, plug-in behaviour, charging demand, and baseline charging behaviour.
4	Use case modelling for three V2G use cases in 2025 and 2030.
5	Final report, summarising the findings from all tasks of the study, and with an assessment of the potential for V2G to accelerate EV adoption in Scotland.

Table 11: The methodology for the project broken down in terms of tasks including a brief description of each task.

11.3 Key definitions

Opportunities have been categorised by vehicle type utilising V2G, daily operation, charging window, local environment, and geographic context. Once opportunities were identified, sources of financial savings were outlined. Additionally, non-financial advantages related to V2G, such as positive impacts on the electricity grid, were identified and clarified. Descriptions for these terms are provided in Table 12.

	Subcategories	Description
Opportunities for V2G	Vehicle type	The vehicle type which is being used as part of the V2G trial
	Daily operation	The type of journey and hours of the day for when the EV is operational
	Charging window	The hours during the day for when the EV is being charged, therefore when V2G can occur
	Local environment	The location where the EV is being charged and where V2G can occur such as at home, public car park or at a depot
	Geographic context	The location of charging local environment, mainly consisting of rural and/or urban locations.
Financial savings	Grid services	Flexibility markets exist to pay assets to balance supply and demand on the electricity grid. To maintain balance, EVs can be used to stop charging (reduced demand on the system) or export power to the grid (increased supply)
	Energy arbitrage	The batteries in EVs make it possible to buy electricity at low prices during the day and sell this electricity at higher prices, typically during the evening. This is accomplished through tariff optimisation or direct participation in the electricity wholesale market
	Integration of on-site renewables	EVs can optimise self-consumption, reducing grid electricity purchases and selling excess electricity at high prices
Other benefits	Reducing curtailment from local renewables	EVs can charge during periods of high renewable generation on their local electricity grid, storing them for periods when there is low renewable generation whereby, they can discharge
	Avoiding use of high-carbon technologies	Flexibility services such as frequency response are typically supplied by gas- or diesel-powered generators which can be turned up or down within short timeframes
	Emergency back-up	EVs can supply emergency power into the grid when there is an outage on the electricity network
	Peak demand reduction	EVs can a reduce power consumption quickly and for a short period of time to avoid a spike in demand on the electricity grid

Table 12: Descriptions of the subcategories used for the V2G opportunities.

11.4 Potential carbon emissions reductions from a fully electrified fleet

The potential carbon savings from a fully electrified fleet were calculated assuming an instantaneous switch from fossil fuel vehicles to electric vehicles for passenger cars, LGVs, buses, HGVs and RCVs. The emissions from charging a fully electrified fleet were calculated using the equation below:

$$\text{Yearly emissions from total electrified fleet (gCO2 per vehicle type per year)}$$
$$= \text{Scottish grid intensity} \left(\frac{\text{gCO2}}{\text{kWh}}\right)$$
$$\times\ \text{Registered vehicles (vehicles per vehicle type)}$$
$$\times\ \text{Average annual energy use}\ \left(\frac{\text{kWh}}{\text{year}}\ \text{per vehicle type}\right)$$

These emissions were then compared to the carbon emissions for a fossil fuel-based fleet using the Scottish total road transport emissions in 2021 and the percentage breakdown per vehicle type [2]. The assumed inputs for the calculations are given in Table 13.

There was no identified data on emissions RCVs in Scotland. To calculate emissions reduction potential, the current UK emissions from RCVs in 2020 [16], the percentage of RCVs in Scotland in 2020 [17] and the percentage of RCVs in Scotland in 2020 [17] were used as shown in Table 13. To determine the emissions reduction potential, the emissions reduction from the use of 1 electric RCV relative to that of a fossil fuel RCV was used [83] and scaled to the number of RCVs within the Scottish fleet.

Value	Input	Source
Total road transport emissions in Scotland for 2021	8.89 $MtCO_2e$	[2]
Passenger car contribution towards road transport emissions in Scotland in 2021	53.3%	[2]
Bus contribution towards road transport emissions in Scotland in 2021	1.2%	[2]
LGV contribution towards road transport emissions in Scotland in 2021	20.2%	[2]
HGV contribution towards road transport emissions in Scotland in 2021	20.6%	[2]
UK emissions from RCVs in 2021	330 $ktCO_2e$/year	[16]
Number of registered RCVS in the UK in 2021	17,800 vehicles	[31]
Percentage of UK HGVs in Scotland 2021	7%	[17]
Scottish grid emissions in 2021	26.9 gCO_2/kWh	[84]
Average annual energy use for passenger cars	1,296 kWh/year	[85]
Average annual energy use for buses	90,000 kWh/year	[86]
Average annual energy use for LGVs	4,405 kWh/year	[19]
Average annual energy use for HGVs	55,555 kWh/year	[19]
Annual reductions from the use of one electric RCV	28,000 $kgCO_2e$/year	[83]

Table 13: The value used for the fleet electrification calculations, the data point used and the source.

11.5 Use case modelling

11.5.1 Duty cycle assumptions

Use case	Average daily mileage (km)	Battery size (kWh)	Electricity consumption (kWh/km)	Charger power (kW)
Domestic passenger cars[9]	30	51	0.16	7
Vans in urban depot[10]	50	82	0.29	7
Trucks in urban depot[11]	90	200	0.90	22
Buses in urban depot[12]	209	300	1.10	80
RCVs in urban depot[13]	100	300	2.33	50

Table 14: The duty cycle assumptions for use cases in 2025

11.5.2 Modelling of additional value

Each of the five use cases charging profiles were modelled to understand the value of participating in a number of flexibility services. The flexibility services considered, and the source of the data used is summarised in Table 15.

Financial value opportunity	Data sources
Energy arbitrage with participation in the wholesale electricity market	Optimisation considered average day ahead prices (£/MWh) over 2021 (deemed most representative year for 2025-30, Wholesale).
Energy arbitrage with participation in the Balancing Mechanism	Optimisation considered system sell and buy prices (£/MWh) in 2018 (deemed most representative year for 2025-30).
Integration of on-site renewables	Solar PV profile [87]. Rooftop size assumed to be 22.5m^2 for domestic,6.46m^2 per EV for commercial [12].
Local DSO flexibility services	Prices based on SPEN April 2023 Auction. Average £/kW/yr for demand service providers awarded contracts. 18:00-21:00 event window assumed.
Consumer flexibility services	£3/kWh (£ 2023) based on 2022/23 &2023/4 ESO base price. 17:00-19:00 event window assumed, 6 events per year.

Table 15: Summary of data sources used in modelling of additional value for each of the use cases.

[9] Sources: average daily mileage [19], battery size, electricity consumption and charger power [21].
[10] Sources: average daily mileage [19], battery size, electricity consumption and charger power [21].
[11] Sources: average daily mileage [19], battery size, electricity consumption and charger power [88].
[12] Sources: average daily mileage [19], battery size, electricity consumption [88] and charger power [89].
[13] Sources: average daily mileage [22], battery size, electricity consumption and charger power [23].

The charge and discharge profiles of each use case was optimised on a half hourly basis over 24 hours. Modelling considered the size of the vehicle's battery in addition to its daily charging demand, to ensure sufficient charge for the daily operation of each use case within the allocated charging window and that the state of charge of the battery remains at least 40% to limit battery degradation and ensure sufficient range if charging window was unexpectedly shortened. The vehicle characteristics of each use case are summarised in Table 16, alongside sources for each. The additional value was calculated in 2025 and 2030 according to the different vehicle characteristics but was assumed to remain constant over the 15-year lifetime of the V2G hardware in the cash flow modelling.

Use case	Metric	Initial year	Value	Source
Domestic passenger cars	Average daily mileage (km)	2025, 2030	30	[19]
Domestic passenger cars	Electricity consumption (kWh/km)	2025	0.16	[21]
Domestic passenger cars	Electricity consumption (kWh/km)	2030	0.15	[21]
Domestic passenger cars	Battery size (kWh)	2025	51	[21]
Domestic passenger cars	Battery size (kWh)	2030	49	[21]
Domestic passenger cars	Charger power (kW)	2025, 2030	7	[21]
Domestic passenger cars	Charging window	2025, 2030	5.30pm – 8am	[24]
Vans in an urban depot	Average daily mileage (km)	2025, 2030	50	[19]
Vans in an urban depot	Electricity consumption (kWh/km)	2025	0.29	[21]
Vans in an urban depot	Electricity consumption (kWh/km)	2030	0.27	[21]
Vans in an urban depot	Battery size (kWh)	2025	82	[21]
Vans in an urban depot	Battery size (kWh)	2030	89	[21]
Vans in an urban depot	Charger power (kW)	2025, 2030	7	[21]
Vans in an urban depot	Charging window	2025, 2030	7pm – 8.30am	[24]
Trucks in an urban depot	Average daily mileage (km)	2025, 2030	50	[19]
Trucks in an urban depot	Electricity consumption (kWh/km)	2025, 2030	0.90	[88]
Trucks in an urban depot	Battery size (kWh)	2025, 2030	300	[88]
Trucks in an urban depot	Charger power (kW)	2025, 2030	22	[88]
Trucks in an urban depot	Charging window	2025, 2030	5pm – 5am	[25]

Buses in an urban depot	Average daily mileage (km)	2025, 2030	209	[19]
Buses in an urban depot	Electricity consumption (kWh/km)	2025, 2030	300	[88]
Buses in an urban depot	Battery size (kWh)	2025, 2030	1.10	[88]
Buses in an urban depot	Charger power (kW)	2025, 2030	80	[88]
Buses in an urban depot	Charging window	2025, 2030	12am – 5am	[25]
RCVs in an urban depot	Average daily mileage (km)	2025, 2030	100	[22]
RCVs in an urban depot	Electricity consumption (kWh/km)	2025, 2030	2.33	[23]
RCVs in an urban depot	Battery size (kWh)	2025, 2030	300	[23]
RCVs in an urban depot	Charger power (kW)	2025, 2030	50	[23]
RCVs in an urban depot	Charging window	2025, 2030	3.30pm – 7am	[25, 89]

Table 16: The use case, metric, initial year, value and source which were used in the additional value modelling.

11.5.3 Cost modelling

A high and low-cost scenario was defined for the use case modelling, considering the costs identified in Appendix 10.4. The cost scenarios are summarised in Table 17.

Cost component	Low scenario	High scenario
Hardware and installation	AC bidirectional hardware and installation premium above that of a smart charger, ca. £/kW 80 – 37 over 2025 - 30	DC bidirectional hardware and installation premium above that of a smart charger, ca. £/kW 270 – 122 over 2025 - 30
Battery degradation	Degradation rate of 0.005% decrease in state of health per discharge cycle (total of 0.73% decrease per year) [79] applied to battery pack cost projections [80]	Degradation rate of 0.04% decrease in state of health per discharge cycle (total of 5.84% decrease per year) [78] applied to battery pack cost projections [80]
Maintenance	Negligible annual maintenance cost	Maintenance cost assumed to be £100/year [73]

Table 17: Summary of the high and low-cost scenarios used in use case modelling.

The hardware and installation costs are calculated considering the cost premium as set out in Table 17 considering the modelled charger power for each use case. The total cost premium of V2G hardware and installation for each use case is shown in Table 18.

Cost scenario	Year	Domestic passenger cars	Vans in an urban depot	Trucks in an urban depot
High	2025	£1,900	£1,900	£5,973
High	2030	£856	£856	£2,690
Low	2025	£570	£570	£1,792
Low	2030	£257	£257	£807

Table 18: Total cost premium (£ 2023) of V2G hardware and installation relative to smart charging for each of the selected use cases under high and low scenarios in 2025 and 2030

The cash flow modelling considers the additional degradation as a result of V2G participation and does not calculate the total degradation of each vehicle's battery including the impact of driving. The modelled annual degradation cost from V2G across low and high scenarios for each use case is shown in Figure 35.

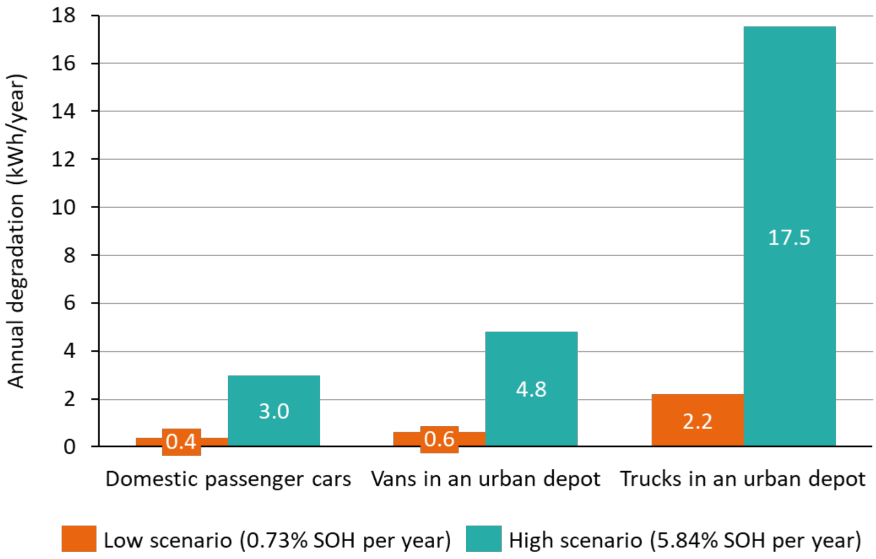

Figure 35: Modelled annual degradation from V2G across low and high scenarios for each use case.

11.5.4 Cash flow modelling

The use case for the selected use cases was assessed through a simple cash flow modelling comparing the additional value and the costs, as described above. The cash flow was modelled over the assumed 15-year lifetime of the hardware [12] and assumed a 3.5% discount rate [90].

The cash flow is calculated for each of the selected use cases assuming the solution is installed in 2025 or in 2030. The cash flow assumes the annual additional value remains constant over the lifetime of the solution.

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Scotland's centre of expertise connecting climate change research and policy

info@climatexchange.org.uk
+44(0)131 651 4783
@climatexchange_
www.climatexchange.org.uk

ClimateXChange, Edinburgh Climate Change Institute, High School Yards, Edinburgh EH1 1LZ

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