

This report provides an evidence-based analysis of future Battery Electric Heavy Goods Vehicle (BEV) charging requirements, geared towards government, energy, and transport stakeholders. The analysis can help in planning future infrastructure investment needs and contribute to ongoing debates on optimum decarbonisation pathways for Scotland.

Towards Zero Emission HGV Infrastructure in Scotland

Phase 2 Technical Report

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Executive Summary

This project uses a high-quality sample of road haulage data within an advanced Agent-Based-Model (ABM), to understand exactly where charging stations need to be built for Battery Electric Heavy Goods Vehicles (BEVs) across Scotland.

This project focuses on en route charging infrastructure in Scotland to service freight transportation by HGVs, for journeys ranging from the relatively short (2-4 hours) to those exceeding 8 hours. The project relies on a representative sample of industry provided journey data, and where this was unavailable, synthetic data was generated.

Key Messages:

1. **Charger Network:** The research reveals a Scottish BEV charger network comprised of 63 en route charger locations, 23 of those being currently operational or under development.
2. **Charger Usage:** The model reveals heavy usage on the A9 (Stirling-Inverness) and M74 (Glasgow-Carlisle), with charger stations on these corridors needing to service approximately 7,000 charging instances requiring in the region of 2,000MWh per annum.
3. **Grid Infrastructure:** Of the 63 identified substations, 80% have sufficient headroom to service nearby charger sites, 2% have marginal capacity, and 18% have insufficient headroom and would require upgrade.
4. **Grid Demand:** Our analysis, using a 2% sample of Scottish HGV journeys, indicates a fully electric HGV network would generate around 143,000 yearly charge events, requiring an additional 1.3 TWh of electrical power.
5. **Operational Changes:** 70% of modelled routes can be completed without additional stops for charging.

1 Introduction

This report focuses on en route charging infrastructure in Scotland for freight transportation by HGVs. In 2024, HGVs travelled around 2.4billion kilometers¹ on Scottish roads, with over half of these by large articulated lorries². Applying the conservative energy consumption assumption used throughout this study (1.7 kWh/km) suggests that, following full electrification, this segment alone would require in excess of 2 TWh of electricity annually. Given the long distances travelled by articulated HGVs, a substantial proportion of this energy demand will need to be met through strategically located en route charging infrastructure.

This report proposes a network of en route charging infrastructure to serve these vehicles, assuring feasibility of operations across diverse geographical regions. The analysis can help government, energy, and transport stakeholders in planning future

¹ Department for Transport. (2025). *Regional Traffic Statistics (Scotland), 1993-2024*. Retrieved from <https://roadtraffic.dft.gov.uk/regions/3>, accessed 1st December 2025.

² Department for Transport. (2025). *Domestic road freight statistics, United Kingdom: 2024*. Table RSF0110, Retrieved from <https://www.gov.uk/government/statistical-data-sets/rfs01-goods-lifted-and-distance-hauled>, accessed 1st December 2025.

investment needs and contribute to ongoing debates on optimum decarbonisation pathways for Scotland.

To achieve this, the report identifies the following:

- Key road haulage routes along which charging infrastructure is required.
- The optimum location for individual charger facilities.
- The impact of charger power on charge and journey times.
- Charger station usage.
- The demands that would be placed on existing grid infrastructure, and where added substation capacity is needed.
- The total power demands placed on the energy system (based on ~2% sample of the total HGV population).
- The potential operational changes required by heavy goods vehicle (HGV) operators.

This project relies on a high-quality representative sample of industry-provided telematics data, and where this was unavailable, synthetic data based on industry intelligence was generated. The study also identifies the potential impacts of eHGVs on the existing grid, highlighting areas where upgrades or reinforcement may be needed due to increased electricity demand. By addressing these key areas, the study provides actionable insights for accelerating Scotland's shift towards a decarbonised freight transport system.

The work was undertaken by the Centre for Sustainable Road Freight (CSRF) at Heriot-Watt University. This is a leading research centre in transport modelling and policy development for decarbonising freight transportation, and is a joint initiative between Cambridge, Heriot-Watt and Westminster Universities. The work was commissioned and funded by Transport Scotland, the national agency responsible for delivering the Scottish Government's vision for transport. This commission is part of a commitment within the HGV Decarbonisation Pathway for Scotland.

2 Methodology

This study adopted a multi-faceted methodology, integrating diverse primary and secondary data with advanced analytical techniques. These are used to develop a robust simulation environment that models the operational transition of Scotland's Heavy Goods Vehicle (HGV) fleet to zero-emission technology.

2.1 Data Sources

The research integrated primary and secondary data, with a crucial enhancement in the quality and sectoral representation of the primary data compared to the previous phase.

2.1.1 Primary Data: Improved Sectoral Coverage of Historical Routes

This analysis began by profiling HGV journeys in Scotland using open-access data from the Continuing Survey of Road Goods Transport (GB)³. This profiling exercise assessed the representativeness of the original dataset. It helped ensure that key industries were appropriately represented in the final dataset by determining where data collection efforts should be focused, and to identifying sectors requiring synthetic data generation.

The result is a significantly more targeted and representative dataset than the initial sample used in Phase 1. Telematics data, representing one year of historical HGV routes, was acquired from fleet operators, now accounting for approximately 2% of Scotland's total HGV population. This provided granular insights into real-world operational practices.

As illustrated in Figure 2.1, the combined sample data (original and newly sourced) is a much better representation of the overall HGV population than the initial sample alone. The current dataset provides good coverage across the majority of industries operating trucks on Scottish roads, with particularly strong representation in the Transportation and Storage sector (+12pp, over-represented) and Wholesale and Retail Trade (+8pp, over-represented). Coverage has also been bolstered in Manufacturing (+8pp) and Agriculture, Forestry, and Fishing (+8pp, achieved with synthetic data generated from secondary sources). However, it is noted that data for the Mining and Quarrying sector is currently not reflected.

³ Department for Transport (2023) Continuing Survey of Road Goods Transport Great Britain: respondents' section. Available at: <https://www.gov.uk/government/statistics/continuing-survey-of-road-goods-transport-gb-respondents-section> (Accessed: 26 February 2026).

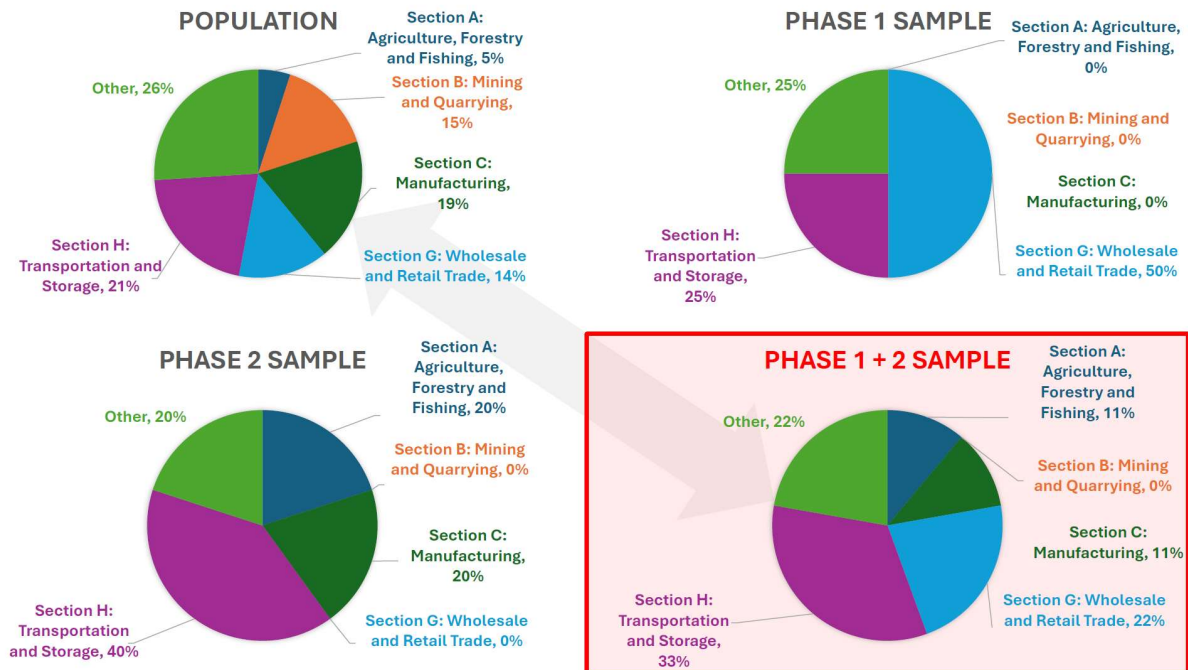


Figure 2.1 Actual profile of HGV journeys in Scotland and the data analysed in Phase 2. Sector classification follows the Standard Industrial Classification (SIC) codes⁴.

2.1.2 Secondary Data: Infrastructure and Grid Capacity

Infrastructure: The core charging network used for the simulation was significantly updated for this phase. The original Phase 1 network was based on existing strategic infrastructure (indicated by circles in Figure 2.2) such as truck stops, lorry parks, intermodal hubs, and ports. These locations were chosen as they already offer existing facilities and amenities (e.g., toilets and cafes) that can be leveraged for charging purposes.^{5,6} It is important to note that these potential locations were not influenced by any existing company plans to install electric HGV chargers. This report utilises an updated network that incorporates several key enhancements. The class of Heavy Duty Vehicles includes HGVs as well as other large vehicles such as busses and bin lorries:

- **WattRoutes:** Findings from the WattRoutes analysis conducted at the University of Strathclyde⁷ added three potentially useful charging locations (indicated by squares in Figure 1.2) that were not included in the initial map.

⁴ Companies House (n.d.) Standard industrial classification of economic activities (SIC). Available at: <https://resources.companieshouse.gov.uk/sic/> (Accessed: 26 February 2026).

⁵ Wu, Y., Lu, Y., Zhu, Z., & Holguín-Veras, J. (2023). Optimizing electric vehicle charging infrastructure on highways: A multi-agent-based planning approach. *Sustainability*, 15(18), 13634.

⁶ Kiani, B., Ogden, J., Sheldon, F. A., & Cordano, L. (2020). Utilizing highway rest areas for electric vehicle charging: economics and impacts on renewable energy penetration in California

⁷ L. C. Hunter, J. Scobie, C. McGarry, & S. Galloway, (2024). WattRoutes: smart planning for electric HGV charging infrastructure. In IET Conference Proceedings CP890

- **Organisational Plans:** The network also integrates existing and planned HDV charging locations announced by various organisations^{8, 9, 10} (indicated by triangles, pentagrams, and stars in Figure 1.2).

This combined approach results in the expansive set of en route charger locations shown in Figure 2.2. It is assumed that land within an approximate 5 km radius of these proposed locations (circles and squares) will be required to install the necessary rapid chargers and provide adequate space for HGVs to park and charge. The charging network has been modelled exclusively across Scotland, and the UK Department for Transport (DfT) are aware of this work so that broader UK-wide modelling can draw on this information. Appendix A: Charger locations contains the precise geographical coordinates for the locations detailed in Figure 2.2.

⁸ Innovate UK Business Connect (2025) ZEHID Slides. Available at: <https://iuk-business-connect.org.uk/wp-content/uploads/2025/03/ZEHID-Slides.pdf> (Accessed: 26 February 2026).

⁹ First Bus (n.d.) Electric vehicle charging partnerships. Available at: <https://www.firstbus.co.uk/about-us/electric-vehicle-charging-partnerships> (Accessed: 26 February 2026).

¹⁰ Ember (n.d.) Charging. Available at: <https://www.ember.to/charging/> (Accessed: 26 February 2026).

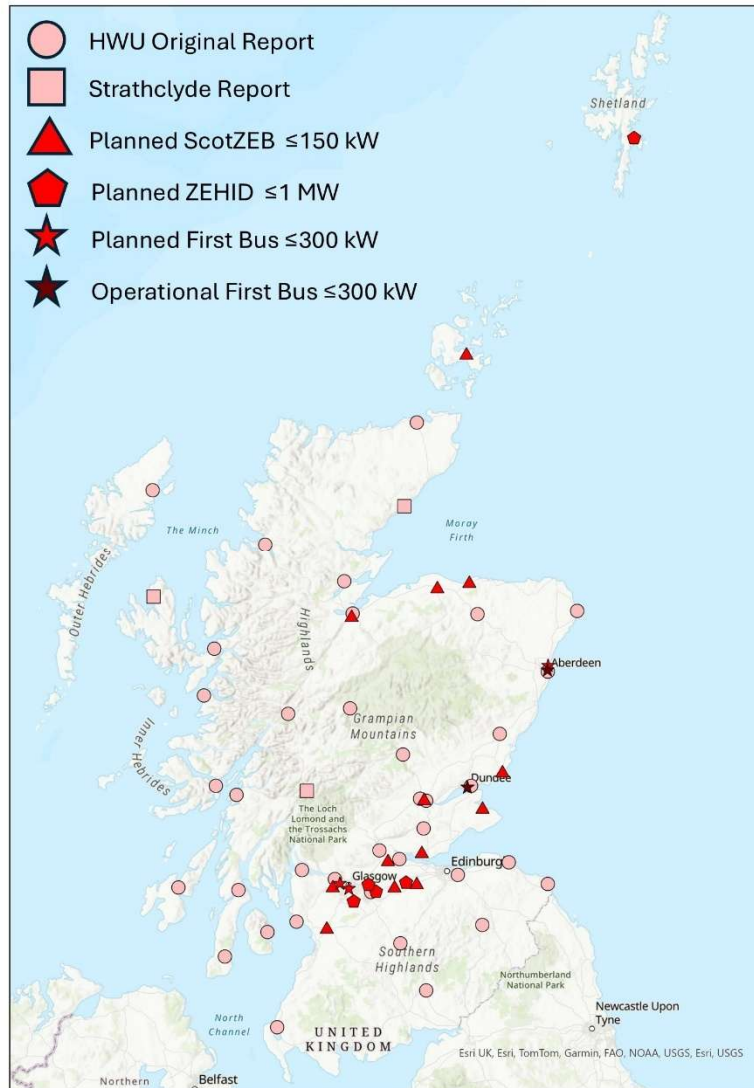


Figure 2.2 Suggested locations of en route infrastructure, combining proposal from Phase 1, Strathclyde and various organisations

Grid Capacity: Openly available data on electricity substations and their forecasted headroom (unutilised capacity) for the 2030 horizon was obtained directly from the primary Distribution Network Operators (DNOs) in Scotland *i.e.*, SP Energy Networks (SPEN) and Scottish and Southern Energy Networks (SSEN).

2.2 Data Collection, Cleaning, and Fusion

The data collected for this research primarily originated from fleet operators within the retail sector and third-party logistics companies. These organisations provided data in CSV or Microsoft Excel formats, encompassing two main categories: Telematics Data and Route Scheduling Data.

2.2.1 Data Categories

- **Telematics Data:** This is a granular dataset capturing individual HGV movements, presented as CSV files where each row represents an automatically logged "event" during an HGV's journey. Relevant fields included Event Type (e.g., ignition on/off), Vehicle Identifier, GPS Coordinates, Timestamp, and Odometer Value.

- **Route Scheduling Data:** This data was generated by fleet operators for route planning purposes. Relevant fields included Start and End Locations (full address with GPS coordinates), and Journey Start and End Times. This data did not contain information on the specific routes taken, as these were determined by driver discretion. Similarly, all times were expected times.
- **Synthetic data:** Data from the Timber Transport Forum (TTF) was used to generate synthetic data for the forestry sector. This data was gathered from Timber Transport Officers in the Argyll and Scottish Borders regions, and gave specific routes travelled by timber haulage HGVs (between forest exits and, for example, sawmills), as well as an approximate maximum number of vehicles travelling each route at any one time. Working with representatives from Scottish Forestry, sawmills and the TTF, it was established that there were approximately 600 timber haulage HGVs working in Scotland. Approximate working times were also established. For each day of the year, each of these 600 vehicles was randomly assigned a single route, giving a “there and back” journey, with each route not exceeding the maximum number of vehicles given in the TTF data. Note that while the 600 vehicles is more than will work in these two regions, this is balanced by the model only assigning a single journey to each truck; in practice they will perform multiple journeys each day.

2.2.2 Data Cleaning and Processing

The raw data underwent a comprehensive cleaning and fusion process, executed using Python, following best practice in telematics data cleaning. It also prepared the data for the MILES model, including extracting relevant underlying features

- **Event Filtering:** Events that did not occur at loading or unloading destinations, such as driver breaks or refuelling stops, were automatically flagged, and then validated via Google Streetview before being removed. This focused the data exclusively on departure and arrival times, enabling accurate representation of trip durations and distances.
- **Odometer Validation:** Instances where the odometer value changed between consecutive "ignition off" and "ignition on" events were analysed to identify potential inconsistencies.
- **Redundant Record Removal:** GPS blips (where GPS locations changed but the odometer remained static) were addressed. These redundant records were either merged or further analysed to determine distinct locations.
- **Location Granularity Adjustment:** GPS coordinates were replaced with postcodes to improve model efficiency and minimise the impact of imprecise GPS data. This step also aided in identifying missing journeys and stop locations.
- **Depot Identification:** The most frequently visited locations by each HGV were identified as depots and formally verified by the fleet operators.
- **Origin-Destination Extraction:** When not explicitly provided, journey origin and destination points, including drop-offs and pick-ups, were derived from the cleaned data.

The combination of automatic processing and stakeholder validation resulted in accurate “Origin-Destination” journey data, with the output CSV files serving as inputs for the subsequent simulation model.

2.3 Simulation Model and Assumptions

Agent-Based Modelling (ABM) is a computer modelling approach that simulates the behaviour of autonomous agents and their interactions. The core analytical engine for this study was the Multimodal Integrated Logistics Environment for Simulation (MILES), an established Agent-Based Model (ABM) developed by the Centre for Sustainable Road Freight (CSRF). MILES was employed to simulate the transition of current diesel HGV routes to Battery Electric Vehicles.

In this study, the agents are individual Battery Electric Vehicles (BEVs). Different rules can be applied to govern agent behaviour; crucially, when a BEV agent requires charging, it seeks locations that minimise both diversion time and distance from its original planned route. As these simulated agents interact according to these rules, collective phenomena such like optimum charger locations, charging strategies, and other key information emerge. This approach represents the state of the art for complex systems problems like transport decarbonisation.

2.3.1 Model Inputs and Infrastructure Network

The cleaned and fused vehicle journey data served as the primary input for MILES. In addition to this operational data, the model required as input the charger network, as described above (Section 2.2.2).

For routes that crossed the border with England, an assumption was made regarding the abundance of charger locations in England, aligning with suggestions from previous studies^{11,12}. This implies that trucks could always find a place to charge in England if necessary, and they were modelled as crossing the border into Scotland with their remaining battery level since the last charging event.

2.3.2 Vehicle Modelling and Constraints

The simulation of Battery Electric Vehicles (BEVs) was based on the following key parameters, aligned with the conservative estimates used in the Route Viability Analysis (Section 3.1). Note that vehicle range can be calculated from battery capacity and energy consumption

- **Battery Capacity:** A 500 kWh battery capacity was assumed for the simulated BEVs.

¹¹ de Saxe, C., Ainalis, D., Miles, J., Greening, P., Gripton, A., Thorne, C., Cebon, D., 2023. An electric road system or big batteries: Implications for UK road freight. *Transportation Engineering* 14, 100210.

¹² Deshpande, P., de Saxe, C., Ainalis, D., Miles, J., Cebon, D., 2023. A breakeven cost analysis framework for electric road systems. *Transportation Research Part D: Transport and Environment* 122, 103870.

- **Energy Consumption:** A conservative energy consumption rate of 1.7 kWh/km was used for the simulated BEVs, corresponding to vehicles fully laden to 44 tonnes.
- **Battery Constraint:** The simulation strictly constrained the usable battery level above 20% State of Charge (SOC). Similarly, the battery was kept below 80% SOC by rapid en route charging, while batteries could reach 100% SOC while slow charging at home depots. This approach was adopted to avoid exceeding manufacturer warranty limitations and aligns with established industry best practice.

2.3.3 Simulation Process and Route Mapping

The MILES model employed the following processes to simulate zero-emission journeys using the Origin-Destination data constructed above:

- **Journey Reconstruction:** Individual vehicle movements were chronologically ordered using time and date stamps. Origin and destination locations were referenced using place coordinate datasets, allowing for the reconstruction and analysis of each vehicle's complete journey history.
- **Route Mapping:** Existing diesel routes were overlaid onto an OpenStreetMap model of the UK road network, with depots serving as start and end points. Vehicle routing was done using GraphHopper, a standard open-source routing engine for OpenStreetMap. GraphHopper considers factors such as road quality to determine the likely average speed for each route segment.
- **En Route Charging Logic:** The model tracked the battery level at each point to determine the necessity of charging. The 'critical incursion point' was identified for each route; this signifies the point at which the driver should consider charging, based on not falling below 30% SOC (for the 500 kWh BEV, this is 150 kWh). This SOC figure comes from the 20% unusable energy level plus a buffer to cover the diversion distance to a charging station¹³.
- **Charger Finding:** All potential stations within a bounded radius (100 km, actual distance not road distance) of the critical incursion point were considered. The model identified the charger that resulted in the least overall route disruption time, including the time required for the route diversion, any overhead time, and the charging duration. This algorithm ran iteratively until a series of charging stops could be identified to successfully complete the route.

2.3.4 Simulation Outputs

The MILES simulation generated a comprehensive dataset of outputs that inform the strategic findings of this report:

- **Aggregated Traffic Flow:** Reconstruction of routes enabled the analysis of aggregated traffic flows, highlighting the busiest corridors.
- **Infrastructure Needs:** The model identified locations where charging stops were necessary. These locations are crucial for the strategic placement of infrastructure.

¹³ Utomo, D. S., Gripton, A., & Greening, P. (2020, December). Long haul logistics using electric trailers by incorporating an energy consumption meta-model into agent-based model. In 2020 Winter Simulation Conference (WSC) (pp. 147-158). IEEE.

- **Operational Impact:** Key metrics such as the number of additional stops required and the increase in total route completion time compared to diesel operations were calculated.
- **Station Utilisation:** The model provided detailed information on the number of visits to each charging station and the total amount of energy delivered to vehicles. This data allows for the assessing of capacity requirements and recommendations regarding staged deployment of charging stations (see Section 3.3).

3 Results and Discussion

This section presents the findings derived from the modelling and analysis conducted during Phase 2, interpreting these results within the context of the strategic goals for zero-emission HGV deployment in Scotland.

3.1 Re-routing

The first objective of this analysis is to determine the proportion of existing HGV operations that can be completed without major operational changes under various charging scenarios, and this is what we look at now.

The analysis assumes that all HGV fleets are fully transitioned to electric vehicles (BEVs). Note that there is currently no clear evidence on the future intentions of individual fleets to enable a more differentiated ratio to be used. The computer simulations assume a 350 kWh usable battery capacity for the modelled HGVs and a conservative energy consumption rate of 1.7 kWh/km. It is important to note that actual vehicle performance in real-world conditions may prove more efficient.

This report explores three distinct charging scenarios to evaluate the impact on routes:

- **Scenario A (Home Depot Charging Only):** Vehicles depart their home depot with a 100% SOC, simulating overnight charging. These vehicles can also re-route to use their own company depots for subsequent re-charging.
- **Scenario B (En Route Charging Only):** Vehicles can re-route to utilise the public charging infrastructure (as detailed in Figure 2.2), charging to a maximum of 80% SOC. For this scenario this is no “overnight” depot charging, so vehicles leave their home depot with the same charge level as when they entered it.
- **Scenario C (Mixed Charge Scenario):** This combined model allows vehicles to utilise both the Home Depot and the En Route charging options.

An exception to these scenarios is applied to fleets based on synthetic forestry transport data, which are assumed to have no dedicated depot infrastructure and, therefore, can only charge en route. This reflects the operational reality where many forestry trucks are operated by individual owner-drivers.

Table 3.1 presents the re-routing details for the three charging scenarios. Re-routing is independent of the specific charger power (the impact of power is addressed in Section

3.2). Routes marked as “unable to complete” were particularly complex and required substantial re-routing, which the model was unable to accommodate at that time¹⁴.

Table 3.1 Route completion and additional stops under each scenario. Routes which were “unable to complete” were complex routes requiring significant re-routing.

Charging Scenario	Home Depot Only	En Route Only	Mixed Charge
% complete with no extra stop	70%	53%	71%
% complete with +1 stop	5%	4%	6%
% complete with +2-3 stops	10%	7%	13%
% complete with 4+ stops	4%	1%	3%
% routes unable to complete	11%	34%	7%

The data clearly demonstrates the critical importance of providing both depot and en route charging for maintaining current operational standards.

When vehicles can charge at their home depot (Scenarios A and C), over 70% of operations remain fundamentally unchanged (*i.e.*, complete with no extra stop). Furthermore, the Mixed Charge Scenario allows fleets to complete significantly more routes than either single strategy, reducing the percentage of overly-complex routes to just 7%.

Conversely, relying only on en route charging (Scenario B) proves highly restrictive, resulting in over 30% of routes requiring significant re-routing. This high percentage of overly-complex routes may necessitate a strategic re-thinking of logistics operations, as necessary re-charging would have to occur during core operational hours, directly impacting efficiency and driver time compliance.

Therefore, the Mixed Charging Strategy offers the optimal pathway, allowing fleets to complete significantly more of their current route portfolio while having the least disruptive impact on existing operational schedules compared to relying on a single charging method.

3.2 Charger Power Analysis

The successful transition to a zero-emission fleet hinges on the rapid recharging of Battery Electric Truck (BET) batteries to maintain tight logistics schedules. This section evaluates the required power capacity at charging hubs, specifically comparing the operational implications of using 350 kW and 500 kW charging infrastructure. While the charger power does not affect route viability (as shown in Section 3.1), it critically influences the overall travel time due to the duration of necessary charging stops.

The modelling incorporates the specified power of charging infrastructure based on its operational status. Specifically:

¹⁴ Subsequent versions of the model can handle these situations.

- The power of existing chargers in the model reflects their current, known specifications.
- The power of planned chargers (those in development) uses their intended power rating (as detailed in Appendix A: Charger locations).
- For proposed new locations that are not yet operational or planned, we conducted two comparative analyses, one assuming the deployment of 500 kW chargers and another assuming 350 kW chargers.

The comparison focuses on the percentage increase in total travel time relative to the original diesel route time. This use of percentage change is essential for meaningful comparison, given the wide variety of route lengths. To mitigate the effect of statistical outliers, routes shorter than 10 km were excluded, and the top and bottom 10% of time increases were removed from the dataset. The median time increase is used to describe the impact on an *"average route"*, as the mean can often be significantly skewed by extreme values.

3.2.1 350 kW Analysis

In this scenario, where new infrastructure is modelled at a maximum of 350 kW, the impact on travel time is notable across all strategies:

- **Home Depot Only:** The necessity of returning to a company depot for charging adds a mean of 122 minutes per route, with the median increase for an average route being 98 minutes (45%).
- **En Route Only:** This scenario adds the most time, with a mean of 127 minutes per route, and the increase for an average route is 124 minutes (43%).
- **Mixed Charging:** This combined approach yields the best performance for 350 kW charging, adding a mean of 93 minutes per route. The increase for an average route is 82 minutes (38%).

3.2.2 500 kW Analysis

The deployment of 500 kW charging infrastructure generally results in a significant reduction in added travel time across all strategies, confirming the operational benefit of higher power:

- **Home Depot Only:** This strategy adds a mean of 105 minutes per route (a reduction from the 122 minutes seen with 350 kW), with the median increase for an average route being 89 minutes (39%).
- **En Route Only:** Relying solely on en route charging increases travel time by a mean of 109 minutes per route (a notable decrease from 127 minutes). The median increase for an average route is approximately 104 minutes (35%).
- **Mixed Charging:** Combining depot and en route charging remains the most efficient strategy, with the mean time increase falling to 78 minutes per route. Crucially, the median increase for an average route is 67 minutes (30%), demonstrating the lowest disruptive impact.

Table 3.2 consolidates the percentage time increases, showing the clear operational advantage of higher power and a mixed charging strategy.

Table 3.2 Extra time required under each scenario in 350 kW and 500kW analyses (as a percentage of original diesel route time).

Metric / Scenario	Home Depot Only	En Route Only	Mixed Charge
Average route time increase (350 kW)	45%	46%	37%
Time increase for average route (Median) (350 kW)	45%	43%	38%
Average route time increase (500 kW)	39%	40%	31%
Time increase for average route (Median) (500 kW)	39%	35%	30%

In conclusion, while the Mixed Charging Scenario is universally the least disruptive, the introduction of 500 kW (or higher) charging infrastructure at newly proposed sites significantly mitigates the time penalty associated with electrification. The lowest median time increase for any strategy is 30%, reinforcing the argument for deploying higher-capacity charging points to ensure logistical efficiency across Scotland’s long-haul network.

3.3 Charger Usage Analysis

This section models the anticipated utilisation rate of the proposed charging infrastructure across key strategic locations. Analysing the expected usage is crucial for appropriate capacity planning and grid connection investments.

The analysis focuses on annual visits to en route chargers and shows that the total number of visits changes very little with the deployment of different charger capacities (350 kW vs. 500 kW). Notably, the expected annual visits per charging site are lower in this Phase 2 analysis compared to the original report. This reduction is primarily due to a larger number of new potential charging station locations having been introduced into our simulation, thereby spreading the total charging demand across a wider network.

Consistent with previous reports, our expanded journey data highlights heavy freight use of key Scottish corridors, particularly the A9 (Stirling-Inverness) and the M74 (Glasgow-Carlisle). Strategically placed en route chargers along these key routes would significantly support BEV journeys, a finding visually confirmed by the utilisation hotspots mapped in Figure 3.1.

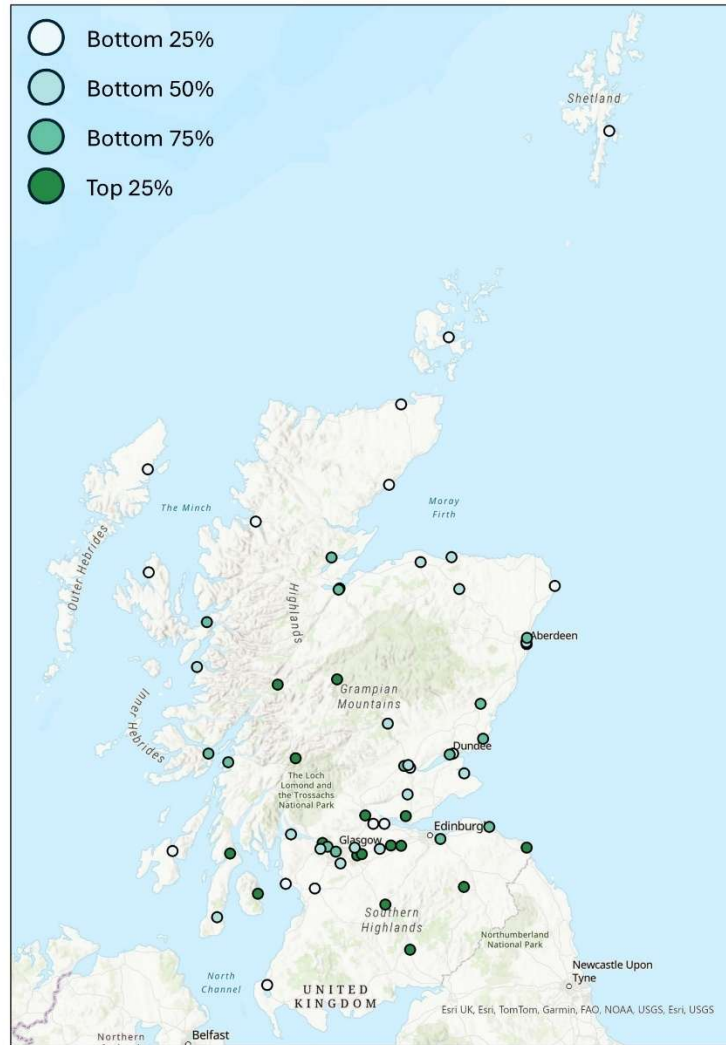


Figure 3.1 Utilisation of en route charging locations for fleets in data set (dark green = more visits)

Although the number of visits remains similar, the 500 kW analysis shows an increase in the total energy delivered by en route chargers for the set of trucks represented in the dataset (a 610 MWh increase, which is less than 1%). This occurs because vehicles utilising the 500 kW option can secure a higher charge in a shorter time, meaning they typically end the day with a higher State of Charge (SOC) than those using 350 kW infrastructure, thus facilitating longer-distance trips.

More charger locations were introduced in the Scottish Islands (specifically Orkney, Shetland, and the Isle of Lewis) for the simulation. However, the modelled utilisation for these locations remains low, reflecting the limited representation of island-based journeys in our current HGV dataset. Nevertheless, suitable BEV chargers will still be required on these islands to support local operations, and we would search for additional data from hauliers currently servicing island routes in the future.

The highest utilisation hotspots are detailed in Table 3.3, quantifying the number of annual visits and the total energy delivered at key locations.

Table 3.3 Top locations for chargers in the model by Number of uses. Scenario: 500 kW, mixed charging.

Location	Number of uses (annual)	Total charge delivered (MWh)
Annandale Water Services	7,431	2,039
Dalwhinnie Service Station	6,832	1,978
Dunfermline	6,529	902
Galashiels	2,371	421
Bathgate	2,338	493
Tyndrum	2,243	392
Mossend Intl Rail freight Park	2,035	163
M8 truck stop Bellshill	1,568	14
Brodick Ferry Port	1,520	268
Eyemouth	1,296	289

3.4 Impact on the Grid Infrastructure

A critical aspect of deploying high-power charging facilities is the subsequent impact on the existing national grid infrastructure. This section analyses the anticipated increased load requirements and identifies areas where grid reinforcement or new dedicated substations will be necessary to support Scotland's zero-emission HGV transition.

The maximum total energy delivered under in all the scenarios was 26.6 GWh; this was the Mixed Charge scenario in the 500 kW analysis (Section 3.2). As the dataset represents approximately 2% of Scotland's HGV fleet, scaling these results suggests that the full electrification of Scottish HGVs would require approximately 1.3 TWh of additional electrical energy annually. It is therefore important to understand how this energy delivery is distributed throughout the electricity grid, and what the peak draws at each location is.

To rigorously assess whether the energy grid can handle the projected optimal charging demand, the nearest primary substation was identified for each proposed charging location. Data sourced from Distribution Network Operators (DNOs) was then utilised to understand the forecasted headroom (unutilised grid capacity) for the 2030 horizon.

Two distinct power draw scenarios were considered to test the grid's resilience:

- **High-Intensity Scenario:** Assumes trucks arrive for charging in **two** peak periods (e.g., morning and late afternoon).
- **Low-Intensity Scenario:** Assumes trucks arrive for charging in **four** peak periods, simulating a more dispersed charging pattern.

For each scenario, the expected total power draw at the primary substation was calculated and directly compared to the forecasted 2030 headroom to identify potential capacity shortages.

The analysis reveals that the majority of substations have sufficient capacity, though a significant minority would require some level of intervention. Figure 3.2 visually maps the

substations, colour-coded based on the comparison between required energy draw and forecasted 2030 headroom:

- Yellow (80% of substations): Sufficient headroom even when subjected to the high-intensity scenario.
- Amber (2% of substations): Sufficient headroom only in the low-intensity scenario, indicating that potential upgrades may be necessary if high-intensity charging were to occur.
- Red (18% of substations): Insufficient headroom even under the most favourable low-intensity scenario, suggesting these sites are highly likely to require significant grid reinforcement.

It is encouraging to note that the percentage of substations falling into the 'Red' category is lower compared to the findings of the original report. This improvement is likely attributable to the inclusion of numerous new charging locations in Phase 2, which effectively distributes the aggregate electrical load across a greater number of substations, thereby alleviating concentration stress points.

It is important to stress that the resulting peak electricity draw calculated here should be considered a minimum estimation, as the current HGV journey dataset represents only about 2% of all Scottish trucks.

The critical substations identified as potential pinch points within the grid infrastructure (those requiring the most detailed technical investigation for reinforcement) include (names taken from DNO datasheets^{15 16}).

- **SPEN:** Gartsherrie, Glendinning Terrace, Larbert, and St. Ninians
- **SSEN:** Bridge of Don, Burghmuir, Dalwhinnie, Lochdonhead, Milnathort, and Mount Pleasant.

While reinforcement is the traditional solution for 'Red' sites, it should be noted that there are situations in which these critical locations can still provide for high-intensity charging by deploying flexibility services (e.g., battery energy storage systems) or on-site generation, thus minimising or delaying costly reinforcement projects.

¹⁵ https://www.spenergynetworks.co.uk/pages/long_term_development_statement.aspx (accessed August 2024)

¹⁶ <https://www.ssen.co.uk/about-ssen/dso/publications-and-reports/> (accessed August 2024)

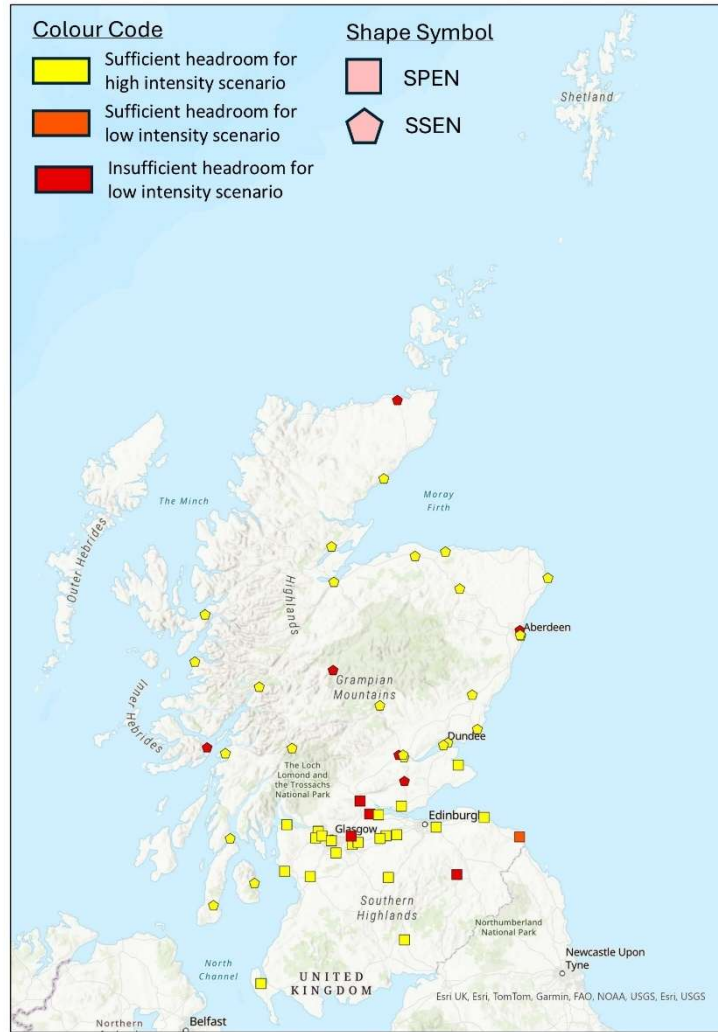


Figure 3.2 Substations beside charge locations, coloured to highlight discrepancies between headroom and required energy

3.5 Complementary Mathematical Analysis

This section provides a quantitative basis for the infrastructure recommendations, specifically evaluating the operational feasibility of deploying Battery Electric Vehicles (BEVs) along key logistics corridors in Scotland and their vital connection points to Northern England. The analysis focuses on determining the necessary location and capacity of charging infrastructure to facilitate a minimum stop route completion, considering the varying performance characteristics of different BEV models under both standard and adverse winter conditions.

The assessment first calculates the minimum number of charges required for a specific BEV model to complete each strategic route. It then validates that the proposed network locations are optimally placed to facilitate this "minimum stop" scenario. Both summer and winter conditions are considered, incorporating both manufacturer specifications for named OEM BEVs and the conservative specifications used for the simulated BEV in the core model.

A crucial parameter in this analysis is the winter range reduction factor of 80%, a value established through real-world trials conducted in England by the Centre for Sustainable Road Freight (CSRF) at the University of Cambridge. This factor is applied to the nominal range to determine a realistic operational range during colder months.

Table 3.4 details the six strategic logistics routes examined; five represent genuine supermarket logistics flows, while the sixth approximates an anonymised route from the report's aggregated dataset.

Table 3.4 Selected Logistics Routes

Origin	Destination	Route
Glasgow Eurocentral	Inverness	M8-M90-A9
Glasgow Eurocentral	Aberdeen	M8-M90-A90
Bathgate	Newcastle	A720-A1
Livingston	Carlisle	M8-M74
Livingston	Cairnryan (ferry port)	M8-M77-A77
Carlisle	Cairnryan (ferry port)	M6-A75

Table 3.5 outlines the key vehicle specifications used in the feasibility analysis. The Computer Model truck reflects the conservative specifications used in the wider computer modelling component of this project, assuming a vehicle fully laden to 44 tonnes. All other ranges are taken from the ZETI tool¹⁷ and represent OEM-advertised range, which often optimises for maximum range at the potential expense of carrying capacity. The Median vehicle represents the median range of all HGVs currently available in the UK market¹⁸. The seven vehicles from named OEMs are the maximum-range variants offered in the UK market¹⁹. As six of these vehicles can comfortably complete all routes analysed, they are grouped into a single "Other" column in the subsequent feasibility tables for simplicity.

Table 3.5 Truck Model Specifications and Ranges

BEV Model	Normal Range (km)	Winter Range (km)
Computer Model	200	160
MAN	600	480
DAF	570	456
Renault	560	448
Scania	520	416
Mercedes-Benz	500	400
Volvo	450	360
Volta	241	193
Median	360	288

¹⁷ CALSTART (2024): Drive to Zero's Zero-Emission Technology Inventory Data Explorer, version 1.5
<https://globaldrivetozero.org/tools/zeti-data-explorer/> version

¹⁸ https://public.tableau.com/shared/89DBCFF2T?:display_count=n&origin=viz_share_link

¹⁹ https://public.tableau.com/shared/25QX5K295?:display_count=n&origin=viz_share_link

3.5.1 Route 1: Glasgow–Inverness

This route covers approximately 290 km, linking the major Eurocentral industrial estate to Inverness via the M90 and the critical A9 trunk road. Three charging locations currently exist or are planned along the route *i.e.*, Kinross, Ballinluig, and Dalwhinnie. The Ballinluig location is geographically central, situated 140 km from Glasgow and 150 km from Inverness, making it an ideal central charging stop (see Figure 3.3). An alternative route variation via the M73 and M80 joins the A9 near Stirling, passing the Stirling Services charger location.

The primary challenge on this corridor is the segment between Ballinluig and Inverness, a long rural stretch that incorporates the Drumochter mountain pass.

As shown in Table 3.6, the complete route is not viable in winter without charging for the Computer Model, Volta, or Median trucks due to range limitations. The Ballinluig–Inverness stretch is only marginally within the Computer Model truck’s winter range (160 km).

Table 3.6 Vehicle Feasibility for Route 1: Glasgow–Inverness (Summer vs. Winter Conditions)

Metric	Computer Model	Volta	Median	Other
Can complete without charger, summer	No	No	Yes	Yes
Can complete without charger, winter	No	No	No (marginal)	Yes
Can complete with 1 charge (Ballinluig), summer	Yes	Yes	Yes	Yes
Can complete with 1 charge (Ballinluig), winter	Yes (marginal)	Yes	Yes	Yes

Recommendation: The charging location at Ballinluig is essential for enabling the majority of the current fleet to complete this corridor year-round. Furthermore, the Dalwhinnie, Stirling Services, and Kinross locations will be required to ensure full route viability, offering critical redundancy in harsh weather conditions and for vehicles operating with sub-optimal energy efficiency.



Figure 3.3 Key distances between routes.

3.5.2 Route 2: Glasgow–Aberdeen

This route covers approximately 250 km, connecting Eurocentral to Aberdeen via the M90 and A90. Three charging locations are identified along this route: Kinross, Dundee, and Stracathro (see Figure 3.4). Dundee is centrally located, 137 km from Glasgow and 116 km from Aberdeen.

Table 3.7 confirms that this route is less challenging than Route 1. It is not viable for the Computer Model in either season without charging, and the Volta model is marginal in summer.

Table 3.7 Vehicle Feasibility for Route 2: Glasgow–Aberdeen (Summer vs. Winter Conditions)

Metric	Computer Model	Volta	Median	Other
Can complete without charger, summer	No	Yes (marginal)	Yes	Yes
Can complete without charger, winter	No	No	Yes	Yes
Can complete with 1 charge (Dundee), summer	Yes	Yes	Yes	Yes
Feasibility with 1 charger (Dundee), winter	Yes (marginal)	Yes	Yes	Yes

Recommendation: The charging location at Dundee is essential to guarantee viability for the Computer Model and to ensure all BEVs can comfortably travel between Glasgow and Dundee in harsh weather conditions. The Stracathro location is not essential for the viability of this specific route, as the 116 km final leg is well within the range of all vehicles

under all foreseen circumstances. The Kinross services, however, are also important for the wider Edinburgh-Inverness corridor.



Figure 3.4 Key distances between route 2 segments

3.5.3 Route 3: Livingston–Newcastle

This route covers approximately 230 km, establishing a critical logistics link connecting the Bathgate/Livingston industrial area to Newcastle in the North East of England via the M8 and the A1. The model incorporates two chargers located along the A1 at Dunbar and Eyemouth. The Eyemouth location is almost perfectly central, situated just under 115 km from both Livingston and Newcastle.

Table 3.8 shows that while many long-range vehicles can complete the route without charging in summer, reliance on the Computer Model and Volta trucks, or facing winter conditions, necessitates a charging stop.

Table 3.8 Vehicle Feasibility for Route 3: Livingston – Newcastle (Summer vs. Winter Conditions)

Metric	Computer Model	Volta	Median	Other
Can complete without charger, summer	No	Yes (marginal)	Yes	Yes
Can complete without charger, winter	No	No	Yes	Yes
Can complete with 1 charge (Eyemouth), summer	Yes	Yes	Yes	Yes
Feasibility with 1 charger (Eyemouth), winter	Yes	Yes	Yes	Yes

Recommendation: The charging location at Eyemouth is essential to ensure continuous and smooth logistics operations between Scotland and the North East of England, especially for the lower-range vehicle models and in winter conditions. Conversely, the Dunbar charging location is not essential for the viability of this specific route, nor is a charger required between Eyemouth and Newcastle, as the 115 km segment is well within the range of all modelled vehicles under all foreseeable circumstances.



Figure 3.5 Key distances between route 3 segments

3.5.4 Route 4: Livingston–Cairnryan

This route covers approximately 170 km, connecting the Bathgate industrial area to the vital Cairnryan Port via the M8, M77, and A77. The most direct route passes a charger at Hamilton (Mossend). An alternative option involves a diversion to the Ardrossan charging location, which breaks the journey into two highly feasible segments of just under 110 km each, but adds approximately 45 km to the total journey distance.

This route is marginally viable for the lowest-range vehicles in summer without charging, but winter conditions make charging mandatory for the Computer Model (Table 3.9).

Table 3.9 Vehicle Feasibility for Route 5: Livingston – Cairnryan (Summer vs. Winter Conditions)

Metric	Computer Model	Volta	Median	Other
Can complete without charger, summer	Yes	Yes	Yes	Yes
Can complete without charger, winter	No (marginal)	Yes (marginal)	Yes	Yes
Can complete with 1 charge (Hamilton), summer	Yes	Yes	Yes	Yes
Feasibility with 1 charger (Hamilton), winter	Yes	Yes	Yes	Yes

Recommendation: One charging location is essential to ensure the full feasibility of this route, including in harsh weather conditions and for vehicles operating with sub-optimal efficiency. While the illustrated route via Mossend is viable in most situations, charging should also be made available on the A77 corridor around Ayr. This would eliminate the need for the significant diversion to Ardrossan, which is otherwise necessary for many lower-range vehicles in harsh weather conditions to complete the journey safely.

Furthermore, it is noted that Cairnryan (Loch Ryan Port) itself is part of the suggested charger network. This is critical for the continued operational viability of the route, particularly for changeover runs and operations where vehicles service the port but do not board the ferries.



Figure 3.6 Key distances between route 5 segments

3.5.5 Route 5: Carlisle–Cairnryan

This route covers approximately 175 km, connecting Carlisle to the key ferry hub of Cairnryan Port via the A75. Crucially, no chargers are currently located directly along this route, although Cairnryan (Loch Ryan Port) itself is part of the suggested charger network, meaning vehicles can charge at the destination.

A diversionary charge is available towards the start of the route at Annandale Water Services. Taking this diversion increases the route length to approximately 205 km, comprising two segments of 148 km and 55 km.

Table 3.10 confirms that while the route is marginally feasible for the lower-range vehicles in summer, the lack of an en route charger makes it non-viable for the Computer Model truck and marginal for the Volta truck in winter conditions. Even with the Annandale diversion, the Computer Model's feasibility remains marginal in winter due to the long initial segment.

Table 3.10 Vehicle Feasibility for Route 5: Livingston – Cairnryan (Summer vs. Winter Conditions)

Metric	Computer Model	Volta	Median	Other
Can complete without charger, summer	Yes (marginal)	Yes	Yes	Yes
Can complete without charger, winter	No (marginal)	Yes (marginal)	Yes	Yes
Can complete with 1 charge (Annandale), summer	Yes	Yes	Yes	Yes
Feasibility with 1 charger (Annandale), winter	Yes (marginal)	Yes	Yes	Yes

Recommendation: Charging should be made available on the A75 between Dumfries and Cairnryan to ensure the full viability of this route, particularly to support lower-range vehicles in harsh weather conditions and those operating with sub-optimal efficiency. Relying on the Annandale Water diversion is operationally sub-optimal due to the added distance.



Figure 3.7 Key distances between route 6 segments

3.5.6 Route 6: Livingston–Carlisle

This route covers approximately 175 km, connecting the Bathgate industrial area to Carlisle via the M8 and the M74 motorway. Three chargers are currently located along the route at Hamilton (Mossend), Abington, and Annandale Water.

The location at Annandale Water is strategically positioned, being only 120 km from Livingston and a very short 55 km from Carlisle. These distances are easily manageable for all vehicle models in all foreseeable circumstances.

Table 3.11 shows that the route is already highly feasible. It is marginally completeable by the Computer Model in summer and marginally viable for the lowest-range vehicles in winter without any charging stops.

Table 3.11 Vehicle Feasibility for Route 4: Livingston – Carlisle (Summer vs. Winter Conditions)

Metric	Computer Model	Volta	Median	Other
Can complete without charger, summer	Yes (marginal)	Yes	Yes	Yes
Can complete without charger, winter	No (marginal)	Yes (marginal)	Yes	Yes
Can complete with 1 charge (Annandale), summer	Yes	Yes	Yes	Yes
Feasibility with 1 charger (Annandale), winter	Yes	Yes	Yes	Yes

Recommendation: While the charging location at Annandale Water is not strictly essential for the sole viability of this route, its presence would ensure that BEVs can travel between the central belt (Livingston/Edinburgh) and the North West of England in harsh weather conditions and when running with sub-optimal efficiency. More importantly, the Annandale Water location is crucial for ensuring smooth logistics operations connecting Scotland with Northern Ireland via the Cairnryan ferry port (as demonstrated in Route 5 and other combined routes), cementing its status as an essential infrastructure component for the wider UK logistics network.



Figure 3.8 Key distances between route 4 segments

4 Conclusion

This Phase 2 Report utilises an advanced Agent-Based Model (ABM), fed with telematics data from approximately 2% of Scottish HGVs and supplementary synthetic data, to provide a rigorous, data-driven framework for the decarbonisation of the nation's long-haul freight sector.

The study confirms several critical requirements for maintaining operational continuity across Scotland's logistics network:

1. **Optimal Charging Strategy is Mixed:** The modelling results demonstrate that a mixed charging strategy (combining home depot charging and en route charging) is essential for fleet viability. Relying on this combined approach allows fleets to complete over 90% of their existing operations effectively, reducing the percentage of overly-complex routes to just 7%. By contrast, relying only on en route charging increases the number of overly-complex routes to over 30%, necessitating a disruptive strategic re-thinking of logistics.
2. **Higher Power Mitigates Disruption:** The analysis clearly shows that the choice of charging power critically impacts operational efficiency. Deploying 500 kW charging infrastructure at newly proposed sites significantly reduces the added travel time compared to 350 kW chargers. Specifically, the optimal mixed charging scenario coupled with 500 kW capacity results in the lowest median time increase, adding approximately 67 minutes (30%) to the average route, reinforcing the necessity of high-capacity charging to meet tight logistics schedules.
3. **Critical Infrastructure Hotspots:** The research precisely identified that the en route charging infrastructure required for a fully electrified Scottish HGV fleet will comprise at least 63 en route charger locations, of which 23 are already built or under development. Usage is predicted to be heaviest on the M74/A9 corridors, with the two busiest charger sites needed within an approximate 5 km radius of Annandale Water and Dalwhinnie, as detailed by their high predicted annual energy throughput (over 2,000 MWh each).
4. **Route Feasibility and Network Gaps:** A detailed complementary analysis of six strategic logistics routes confirms the necessity of specific charging points for year-round operation. For example, the Ballinluig location is deemed essential for viability on the Glasgow–Inverness corridor, while sites between Dumfries and Cairnryan and around Ayr are necessary to mitigate complex diversions for lower-range vehicles in winter conditions.
5. **Energy and Grid Impact:** The full transition will require substantial electrical power, estimated at between 1.3-2 TWh annually. Crucially, the research precisely identified the localised impact of high-intensity charging on the existing electricity grid, highlighting specific substations experiencing significant peak load demands. The results indicate that 18% of the substations near proposed charging sites will experience insufficient headroom even in a low-intensity charging scenario, notably including key sites such as Gartsherrie and Dalwhinnie. These areas require immediate attention for grid reinforcement or the deployment of flexible solutions (e.g., on-site battery storage).

These findings offer tangible benefits by providing fleet operators with an understanding of charging impacts on operational costs, Distribution Network Operators (DNOs) with targeted insights into specific grid locations, and policymakers with a data-driven framework to identify critical infrastructure gaps and investment priorities.

5 Recommendations

Based on the quantitative and operational findings of this Phase 2 study, the following recommendations are put forward to accelerate the zero-emission HGV transition in Scotland:

1. **Prioritise a Mixed Infrastructure Roll-out:** Policy and funding should strongly incentivise the simultaneous development of both high-power en route charging hubs and depot-based overnight charging facilities. This dual approach minimises operational disruption and maximises route viability for the maximum number of fleet operators.
2. **Mandate at least 500 kW Capacity at New Sites:** For all newly developed strategic en route charging hubs, a minimum capacity of 500 kW per charging point should be the deployment standard. This is critical to ensure charging times align with mandated driver rest periods and to mitigate the significant increase in travel time associated with lower power levels.
3. **Target Grid Reinforcement:** Immediate engagement between policymakers and DNOs is required to address the identified 'Red' category substations (e.g., Gartsherrie, Dalwhinnie) where forecasted headroom is insufficient. Funding must be allocated to enable early grid reinforcement or the deployment of flexibility services (such as battery storage) to avoid future capacity bottlenecks that would stall the deployment of essential chargers.
4. **Close Critical Route Gaps:** Infrastructure planning should prioritise closing the charging gaps identified on key corridors, particularly the A75 (Carlisle–Cairnryan) and ensuring charging availability along the A77 corridor near Ayr to eliminate costly and time-consuming route diversions for ferry traffic.

Appendix A: Charger locations

Table A.1 En route charger locations (approximate locations, 5km radius)

No	Place Name	Locality
1	Abington Services	M74
2	Annandale Water Services	M74
3	Ardrossan Ferry Port	A78
4	Ashgrove Filling Station and Restaurant	A96, Huntly
5	Ballinluig Motorgrill	A9, Pitlochry
6	Brodick Ferry Port	Isle of Arran
7	Broxden Services	A9, Perth
8	Campbeltown Ferry Port	A83
9	Clydebank Railway Station	A814
10	Craignure Mull Ferry Port	Isle of Mull
11	Dalwhinnie Service Station	A9
12	Dunbar	A1

13	Dundee Port	A90
14	Edinburgh East	A1
15	Eyemouth	A1
16	Friarton	M90 Perth
17	Galashiels	A7
18	Grangemouth Docks	M9
19	Greenock Port	A8/A78
20	Inverness Seafield	A9/A96/A82
21	Kennacraig Ferry Port	A83
22	Kinross Services	M90
23	Kyle of Lochalsh	A87 Skye Bridge
24	Loch Ryan Port	A77 Cairnryan
25	Mallaig Ferry Port	A830
26	Mossend Intl Railfreight Park	Hamilton M8/M74
27	Oban Ferry Port	A85
28	Peterhead Port	A90
29	Port Askaig Ferry Port	Isle of Islay
30	Port of Aberdeen	A90
31	Skiach Services	A9 Easter Ross
32	Spean Bridge	A82/A86
33	Stirling Services	M80 & M9
34	Stornoway Ferry Port	Isle of Lewis
35	Stracathro Services	A90 Brechin
36	Sutherland and Caithness	A9
37	Thurso Overnight Lorry Park	A9
38	Tyndrum	A82/A85
39	Uig Ferry Terminal	North Skye A87
40	Ullapool Ferry Port	A835

Table A.2 Existing and planned charger locations

No	Place Name	Operator	Funding Scheme	Maximum Expected Power (kW)
1	Aberdeen	First Group		300
2	Bridge of Don P&R	First Group		300
3	Dundee	First Group		300
4	Glasgow (Caledonia Depot)	First Group		300
5	Glasgow (Scotstoun)	First Group		300
6	Arbroath	Stagecoach	ScotZEB	150
7	Dunfermline	Stagecoach	ScotZEB	150
8	Kilmarnock	Stagecoach	ScotZEB	150
9	St Andrews	Stagecoach	ScotZEB	150
10	Buckie	Maynes Coaches	ScotZEB	150
11	Elgin	Maynes Coaches	ScotZEB	150
12	Orkney (St Margaret's Hope)	Maynes Coaches	ScotZEB	150

13	Glasgow Airport	Ember	ScotZEB	150
14	Perth	Ember	ScotZEB	150
15	Larbert	McGill's Buses	ScotZEB	150
16	Livingston	McGill's Buses	ScotZEB	150
17	Inverness	D&E Coaches	ScotZEB	150
18	Harthill	Hairy Haggis Coaches	ScotZEB	150
19	East Kilbride	Haulier	ZEHID	1000
20	M8 truck stop Bellshill	Haulier	ZEHID	1000
21	Coatbridge	Haulier	ZEHID	1000
22	Bathgate	Haulier	ZEHID	1000
23	Lerwick	Haulier	ZEHID	1000