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Feasibility Report**

Technical Report ENG-TR.045

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Executive Summary

This report addresses the need to develop zero emission solutions for heavy road freight vehicles in the UK. This class of vehicle comprises some 200,000 heavy vehicles with gross vehicle weights (tractor plus loaded trailer) in the range of 25 t – 44 t. The work reported focuses specifically on the definition and delivery of a national Electrified Road System (ERS). This system, in combination with a network of static charging sites, would be capable of supporting the use of long distance, heavy haul electric trucks in the delivery of the complex freight logistics operations of the UK. The report describes the development of a set of system performance requirements and the definition of a suitable system topography. It tests the resulting proposition by making value for money comparisons with the possible alternatives.

Across the spectrum of industrial sectors that need to be de-carbonised, long-distance, heavy road freight has long been regarded as one of the more difficult. Whilst a good start on zero emissions transport has been made by the automotive industry (where battery-electric vehicles are fast becoming established as the preferred way forward) and similar inroads are starting to be made in urban delivery vehicles, this success does not translate easily into the long-haul heavy-vehicle sector. Here the loads hauled and the distances travelled require very large amounts of traction energy to be stored on-board the vehicles. This amount of energy is not easily stored in a battery and this suggests that alternative solutions need to be explored.

Hydrogen has, for a long time, been seen as the solution best suited to solving this problem. It suffers, however, from an important drawback. There is a very large energy loss incurred (around 70%) in converting electricity into green hydrogen and then converting it back into electricity at the point of use in the vehicle. This translates into a high price for green hydrogen and puts an additional, and unwelcome, burden on the national programme for building new sources of renewable power generation.

A possible alternative to both hydrogen and pure battery-powered vehicles for long-haul freight is an electrified road system. This provides charge-on-the-move, via overhead wires and a roof-mounted pantograph, to otherwise conventional battery-powered vehicles. By this means, electric vehicles can be conferred with an operating range which is limited only by the length of the ERS. Using this approach, vehicles with quite small batteries could reach anywhere in the country, thus reducing the cost and weight of each vehicle whilst simultaneously removing all concerns about range. Assuming the sources of electricity on the grid are 'green' the result, in theory, is a zero emissions system with great operational flexibility.

In practice, however, it is not economic to deploy overhead wires on all parts of the national road network. Not all parts of the country will be fully covered by the ERS and, in these areas, a supplementary system of static charging sites must be provided so that vehicles can stop, if necessary, to re-charge their batteries whilst they are operating off the ERS system. This solves the battery state of charge problem, but it introduces an operational constraint because of the time lost whilst charging (often up to 45 minutes). This might delay subsequent deliveries or, in some cases, lead to a requirement for more vehicles making more journeys in order to maintain existing delivery schedules.

This report explores the specification and delivery of a national system which balances the conflicting demands of cost and operational flexibility. It finds that an ERS system of some 5,500 single lane-km (Figure 1) concentrated on those motorways and trunk roads which are most intensely used by heavy-freight vehicles, and supplemented by up to 2,100 static charging stations, represents an infrastructure which is capable of supporting UK logistics operations without requiring any significant changes to current operational practice.



Figure 1: An ERS network of 5,500 single lane-km, supplemented by up to 2,100 static charging stations, would support the UK Logistics industry without requiring any significant changes to current operational practice.

Construction and commissioning costs are estimated for this system and an illustrative programme for building-out the infrastructure is described. This programme is delivered in stages. Stage 1 is scheduled for completion by 2032 and comprises the full 5,500 single lane-km ERS system but with limited power capacity. Stage 1 also includes some 1,000 static charging stations. This initial limit on power delivery reflects the relatively small number of vehicles which will need to use it in the early years, but the system needs to be rolled-out as early as possible in order to give country-wide support to the early adopters of electric freight vehicles. Once the number of ERS-enabled vehicles exceeds 25% of the entire heavy vehicle parc, Stage 2 is implemented. This comprises a continuing programme of ERS system power upgrade, plus an extension of the static charging sites to the full complement of 2,100 sites. Stage 2 is fully complete by 2045.

If this delivery programme is followed, and assuming the electricity grid becomes zero emission by 2040, it is calculated that heavy road freight emissions in use can be progressively reduced from the current tail-pipe levels of around 20 MtCO₂e per annum to zero in good time before the UK Net Zero target date of 2050. This would result in a saving of around 224 Mt CO₂e compared to the continued use of diesel vehicles throughout the intervening period although it would be countered, to some extent, by the embodied emissions associated with the vehicle batteries and the fixed infrastructure. The table below summarises these findings and shows that the majority of the embodied CO₂e lies in the vehicles rather than the fixed infrastructure. This is because the processes associated with battery manufacture result in a high level of embodied CO₂e. Batteries also have other environmental disadvantages which are associated with the materials used in their construction (lithium, cobalt, etc). These considerations underline the benefits of adopting a system which can minimise battery sizes.

	Emissions in Use [MtCO ₂ e]	Embedded Emissions in Vehicle and Charging Infrastructure [MtCO ₂ e]	
		Vehicle Base (500 kWh Battery)	Charging Infrastructure
Diesel 'Benchmark' Fleet	406	-	-
Electric Vehicle Fleet	182	26	-
ERS Light (5,500 STK)	-	-	1.4
Static Charging Network (2,100 Sites)	-	-	0.24
Net Saving/(Expenditure)	224	(26)	(1.64)
Net Benefit/(Disbenefit) over 25 years	~196 MtCO₂e		

Table 1: Summary of the CO₂e emissions savings which would result from the adoption of the proposed ERS delivery programme from 2025-2050.

Despite the positive arguments in favour of ERS, several key difficulties are highlighted including the need to build-out Stage 1 of the system and achieve operational status by 2032. This target is dictated by the need for the charging infrastructure to precede the volume adoption of electric heavy vehicles but it creates a very difficult challenge from the construction delivery perspective. This could require, amongst other things, changes to the way in which major road projects/programmes are procured in future.

The ERS challenge is not unique, however, in its demand for re-thinking and accelerating construction practices. There is a much wider and more pressing need for programmes to be foreshortened in the UK if the nation is to meet its 2050 Net Zero targets. This need is best illustrated by the imperative to build new power generation and transmission/distribution capacity. In national terms, this is a much bigger challenge than that of delivering the ERS/static charger infrastructure within short timescales.

The Business Case associated with ERS is assessed using a triple bottom-line approach based on financial, environmental, and social metrics. The financial case is studied from two different points of view. The Total Cost of Ownership (TCO) of the vehicles over a 6-year first-life is studied through the eyes of the vehicle fleet operators (VFO's) and the revenue generated through building and operating the infrastructure is studied through the eyes of a national system developer/operator. Balancing the commercial needs of the two parties suggests there would be a good return to be made in building-out the proposed ERS/static charger infrastructure, but the unquantifiable risks to a speculative developer might be unacceptably high at the outset. The possibility of the government taking the position of the ERS infrastructure developer/operator is therefore also examined. In this case, a simple comparison is made between the cost of building an ERS infrastructure and the cost of subsidising hydrogen at the point of use so that both solutions have the same TCO as a conventional diesel fleet. Under these circumstances, it is found that it is less costly to build the ERS infrastructure than it is to subsidise hydrogen for all but the most extreme cases. On the downside, the ERS solution requires a large at-risk investment to launch the system, but this is no greater than the similar challenge which is faced by the adoption of (for example) a hydrogen solution.

The environmental aspects of the business case are assessed on the basis of emissions in use and embodied emissions. The results have been summarised in Table 1. It is concluded that a national ERS system has strong environmental credentials and a potential cost advantage over the alternative options.

The social aspects of the business case are presented in terms of the numbers of direct jobs created and the anticipated duration of employment. It is estimated that:

- 7,000 – 8,000 site-based workers per year will be required over the period of the Stage 1 build-out (2028 – 2032).
- 1,000 – 2,000 site-based workers per year will be required over the period of the Stage 2 power upgrading (2035 – 2045)
- 500 - 1,000 factory-based manufacturing workers per year will be required over the period 2026 – 2045 (with potentially many more in the extended materials and components supply chains)
- 500 - 1,000 professional services workers per year will be required in the fields of design, accountancy, project management, etc., with the peak in the early years of designing Stage 1 (2026 – 2032) and the reduced number for the duration of the Stage 2 build-out (2035 – 2045)

Following the business case assessment, the report addresses the questions of funding/financing and stakeholder engagement. Several different funding models are found to be credible and stakeholder engagement is found to be particularly important given the nationwide footprint of an ERS system. Beyond the engagement of the logistics industry and its vehicle suppliers, there is a clear need to win broad social and political support for what would be seen as a National Challenge from a planning and delivery perspective.

1. Introduction

Road freight plays a vital part in the national economy. The logistics of moving goods continuously from point of origin, via warehouse and distribution centres, to retail outlets, industrial sites, and a wide range of different end-users, is a highly developed business. Just-in-time deliveries form the backbone of manufacturing and retail distribution operations around the country. The system is highly optimised and very efficient. It is, however, disproportionately responsible for the emission of transport-related Greenhouse Gases (GHGs) and, as a result, this sector requires serious attention in the national drive to achieve net zero emissions by 2050.

Road freight vehicles can be split into two families. Light Goods Vehicles (LGVs), less than 7.5 t Gross Combination Weight (GCW) and includes almost all ‘white vans’, and Heavy Goods Vehicles (HGVs), greater than 7.5 t GCW. The HGV family comprises approximately 400,000 vehicles in the UK and is populated with a range of rigid and articulated vehicle types. Approximately half these vehicles lie at the heaviest end of the spectrum (25 t – 44 t) and this segment is responsible for approximately half of all HGV consumption and emissions. These vehicles, referred to collectively hereafter as ‘heavy lorries’, represent a particularly difficult de-carbonisation challenge. The breakdown of all vehicles in the HGV sector which has been assumed in this project is shown in Table 1.1. It should be noted that practically all vehicles in the range 25 t – 44 t would be of a size that would enable a pantograph to be mounted on the vehicle – either as original equipment or as a purchaser specified ‘extra’.

Vehicle Size/Type	Population	Average Daily Range per Lorry [km]	Mileage [km]	Fuel Cons. per Lorry [l]	Annual		
					Fleet Fuel Cons. [l]	Fleet CO ₂ Emissions [tCO ₂]	Fleet Energy Cons. [TWh]
7.5 – 14 t Rigid	139,732	112	28,000	6,938	969,459,345	3,150,743	10.24
7.5 – 14 t Artic	489	264	66,000	20,948	10,243,381	33,291	0.11
>14 – 17 t Rigid	22,180	112	28,000	8,692	192,778,558	626,530	2.04
>14 – 17 t Artic	215	264	66,000	20,948	4,503,736	14,637	0.05
>17 – 25 t Rigid	57,055	176	44,000	13,083	746,454,477	2,425,977	7.89
>17 – 25 t Artic	2,005	264	66,000	20,948	41,999,958	136,500	0.44
>25 – 33 t Rigid	68,064	172	43,000	18,129	1,233,933,251	4,010,283	13.04
>25 – 33 t Artic	9,190	264	66,000	20,948	192,508,534	625,653	2.03
>33 t Rigid	5,387	172	43,000	18,129	97,661,002	317,398	1.03
>33 t Artic	109,143	372	93,000	33,253	3,629,378,736	11,795,481	38.34
Total	413,460				7,118,920,977	23,136,493	75.20
Heavy Lorries (>25 t)	191,784				5,153,481,523	16,748,815	54.44

Table 1.1: UK HGV statistics (source: private discussions).

Vehicles in the segment between 7.5 t – 24 t generally operate in urban environments with relatively short-range journeys. Consequently, they are amenable to ‘standard’ automotive battery-electric solutions. Vehicles in the heavier range, however, require something different.

1.1 Scope

The work presented in this report is exclusively concerned with the reduction of GHG’s from heavy lorries. It explores the possibility of developing a national Electric Road System (ERS), proposes the configuration of a ‘Preferred System’ and compares the cost and efficacy of this system with the credible alternatives.

1.2 Structure

The report begins with some contextual background (Chapter 2) and then introduces the logistics considerations (Chapter 3) which quantify the need for, and define the shape of, UK heavy road freight operations. Chapter 4 examines the impact of an ERS system through the eyes of a vehicle fleet operator and introduces the concept of Total Cost of Ownership (TCO). Chapters 5 and 6 address the definition, cost, and delivery of a national ERS infrastructure and Chapter 7 addresses the Business Case which can be made in support of the national roll-out of such a system. In this chapter, comparisons are made with alternative solutions based on arguments of national benefit and cost. Chapters 8 and 9 deal with the important subjects of funding/financing and stakeholder engagement and the report concludes with a series of conclusions and recommendations for further work in Chapter 10.

2. Setting the Context

A straightforward battery-electric solution is not easily applied to lorries in the heaviest segment because these vehicles use high levels of power for long periods of time due to the large payloads being moved and long distances travelled. The batteries required to store the amount of energy used each day by a vehicle would be very large, creating both a cost and a weight penalty. Based on today's battery products, this would be unacceptable. In the absence of a step-change in battery technology, an alternative approach is required.

2.1 Technical Options

Several possible technical solutions exist to decarbonising this part of the transport sector, principal amongst which are:

- lorries using internal combustion engines (ICE) with bio-fuels or synthetic fuels,
- electric lorries using 'electric roads' as a source of external energy supply,
- electric lorries using hydrogen as a source of on-board energy supply.

Bio-Fuels are not investigated in the remainder of this report because there is a natural limit to the supply of feedstock which can be produced in the UK and, at international scale, the very large-scale production required would compete for land with food crops. In the UK it is considered here that it would be better to relinquish the possibility of using bio-fuels for road freight applications and use the limited supply of this fuel for other 'hard to abate' transport applications such as aviation, shipping, and agriculture. (The IEA, in its *Energy Technology Perspectives, 2020* suggests that, for these reasons, bio-fuels will only supply around 10% of the worldwide energy which will be demanded by heavy road freight applications over the period 2019-2070).

2.2 GHG Reduction Profiles

The annual GHG reduction profile and the aggregated emissions are calculated for the period 2025 – 2050 based on the postulated annual sales and market penetration rates for Zero Emission Vehicles (electric/hydrogen) which are shown in Figure 2.1. This is considered to be an 'aggressive' growth scenario (rather more aggressive than the government's current position which calls for no more diesel vehicles to be sold after 2040). The total annual sales of heavy vehicles is assumed to remain constant at around 8% of the heavy vehicle parc per year (the historical average). Even under these rather ambitious assumptions, it still requires around 15 years for the penetration of ZEVs to reach 100% of the heavy lorry parc.

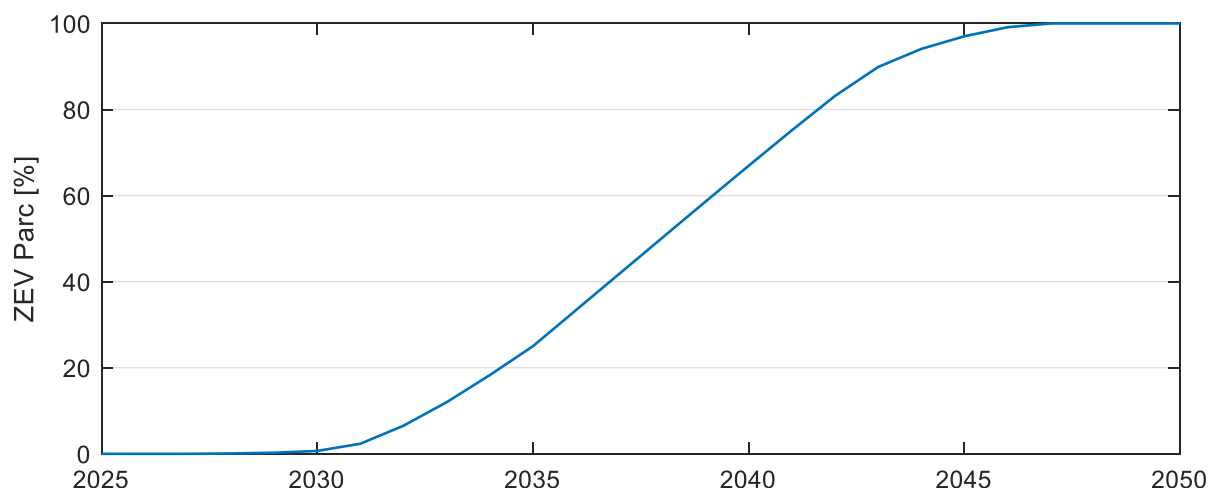


Figure 2.1: Assumed uptake of ZEVs across 2025-2050, as a percentage of the total UK HGV parc.

Following the calculation logic summarised in Appendix A, the annual and cumulative CO₂e 'emissions in use' for the Heavy Lorry parc (i.e. accounting only for those emissions which arise directly during use and excluding the CO₂e embodied in the vehicles and their charging infrastructure) are presented in Figure 2.2 below.

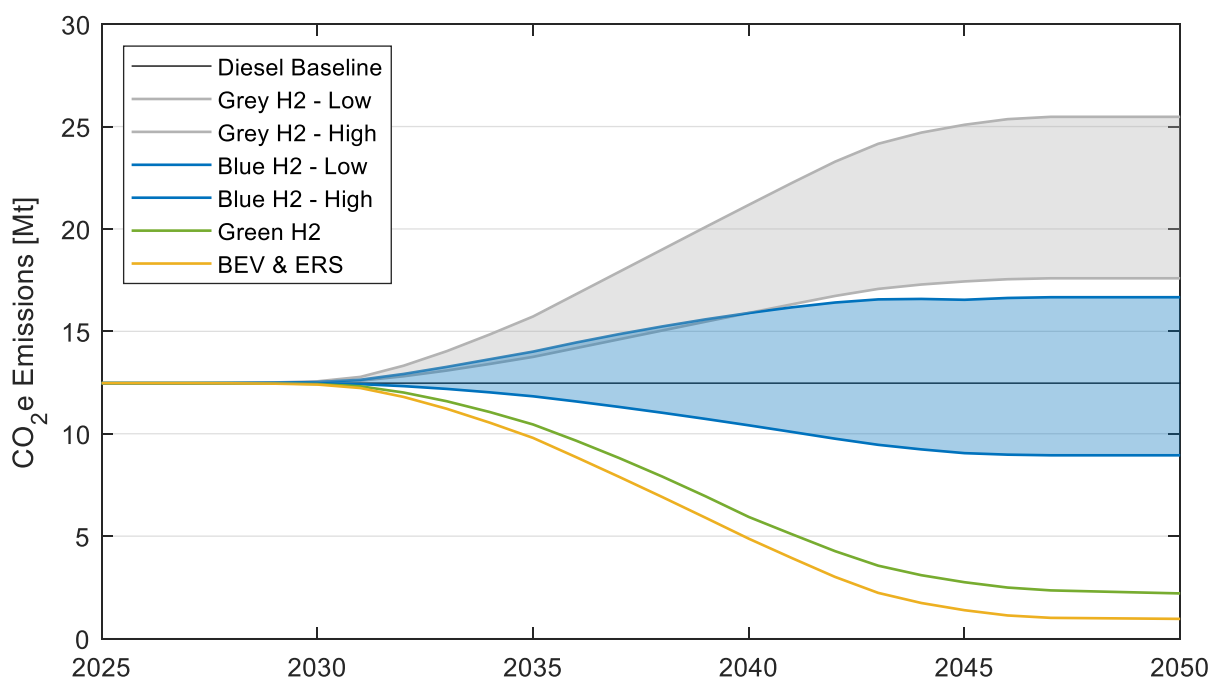


Figure 2.2: Predicted annual in use CO₂e emissions of HGVs for various technology solutions.

The following conclusions can be drawn:

1. There are wide bands of uncertainty regarding the CO₂e intensities of both grey and blue hydrogen. Even under the most optimistic assumptions, using grey hydrogen leads to worse emissions than continuing to use diesel and using blue hydrogen fails to lead to a 'Zero Carbon' solution.
2. Only Green Hydrogen and battery-electric (with, or without, ERS) provide a convincing route to zero emissions.

2.3 Energy Considerations – Green Hydrogen vs Batteries

The amount of green hydrogen required to power the heavy lorry fleet requires nearly three times the amount of renewable energy to be generated at source than that which would be used by battery-electric vehicles for the same purpose. This arises because of the poor 'round-trip efficiency' associated with generating and using hydrogen an intermediate energy vector rather than using the electricity directly. This inefficiency mainly comes from the fact that the best large-scale electrolysis processes are currently around 75% efficient and the best vehicle-proven fuel cells are around 50% efficient.

The combination of these losses leads to the following conclusions:

- Green hydrogen will, in most cases, lead to a more expensive solution than one where electricity is used directly.
- Building and commissioning the additional sources of power generation which are required to produce green hydrogen in the UK will place a further, unwelcome, burden on the already pressing need to build more renewable power.

3. Logistics Considerations

3.1 Introduction

In this chapter, the configuration of a national ERS system is considered based on the logistics needs which it must serve. The identification of a suitable configuration provides the platform for the technical and economic assessments which are developed in Chapters 5,6 and 7. To perform a rigorous logistics assessment, it is necessary to understand and model the journeys which need to be undertaken by lorries which operate across the country in many different economic sectors. This will enable the balance between battery sizes and charging infrastructure to be determined.

To perform this analysis, the following parameters need to be established:

- The make-up of the UK heavy lorry parc, so that the investigation can be narrowed-down to the most important sectors
- The types of journeys undertaken so that battery capacities, charger power and charger locations can be specified.
- The origins and destinations of journeys, so the off-ERS components of journeys can be understood and modelled. (It is unrealistic to propose that ERS capabilities are installed *everywhere* so, in any practicable scenario, there will be a large fraction of the Strategic Road Network which is not electrified).

This chapter details the data sources used and the analysis undertaken to address these issues.

3.2 Distribution and Ownership of Vehicles

The first step in this process is to describe the fleet by vehicle type, sector and ownership. This analysis provides a framework for understanding which sectors operate which types of vehicles and in what quantities. The results will subsequently be used to weight the journey descriptions. Table 1.1 presented in Chapter 1 summarises the number of vehicles in each category and shows their emissions contribution to the total emissions from freight transport. The table shows that vehicles over 25 t represent around 50% of the total fleet and vehicles over 33 t represent about 25% of the total fleet. This highlights the importance of decarbonising the heaviest vehicles.

Unfortunately, there is no easily accessible data detailing the ownership of the UK HGV fleet. However, it is possible to estimate the fleet ownership using several disparate sources of data. These data describe: the largest fleets by company, the logistics activity by sector, and the warehouse space by sector.

Table 3.1 below summarises the 25 largest fleets in the country. This fleet data excludes the third-party logistics providers (3PL's) and the groupage sector and shows that, barring these operators, the construction sector has some of the largest fleets. The construction sector, however, operates a range of different vehicle types. On closer inspection, the Saint-Gobain and Travis Perkins fleets are biased to smaller HGVs delivering to builders' merchants on a just in time basis and these movements are not relevant to the current study. Neglecting these operators modifies the list and identifies the food and retailer sectors as the large fleet operators. These sectors are dominated by the supermarkets.

Rank	Operator	Number of Vehicles
1	Saint-Gobain	2,947
2	Veolia	2,732
3	Travis Perkins	2,357
4	Tesco Distribution	1,679
5	Brake Bros	1,564
6	Sainsbury's	1,450
7	Asda Stores	1,345
8	3663 Transport and BFS Group	1,204
9	Muller UK & Ireland	1,188
10	Warburton	945
11	BT Fleet	937
12	John Lewis	906
13	Certas Energy UK	872
14	G4S	836
15	Palmer & Harvey McClane	772
16	The Co-Operative Group	726
17	Kier MG	720
18	ABF Grain Products	714
19	Biffa Waste/Municipal	707
20	Sita UK	692
21	SIG	638
22	Calor Gas	573
23	BOC	532
24	WM Morrison	516
25	Berendsen UK	413

Table 3.1: Numbers of HGVs in the UK's largest fleets, excluding 3PLs (source: Motor Transport).

The data does not discriminate between different vehicle sizes, and it is necessary to use a set of assumptions to develop a meaningful insight into the key sectors operating large HGVs. Alternative sources of data suggest similar conclusions. Figure 3.2 identifies the largest own-fleet operations in the UK and, if the construction sector is once again excluded because of its skew towards smaller vehicles, the figures confirm the previous analysis that the sector with the biggest fleet is the food sector.

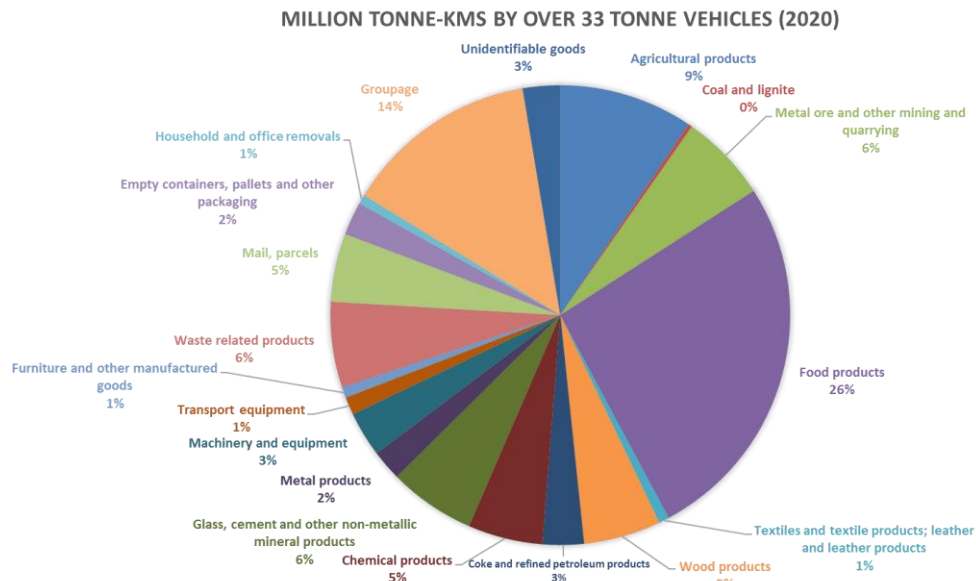


Figure 3.2: Transport work in t.km by UKL HGVs heavier than 33 t (2020).

Intuition suggests that some sectors will be more important than others when considering the focus of this project on very heavy vehicles. The analyses reported here suggest that the food sector accounts for the largest single proportion of the total freight moved. Furthermore, it can be seen that 49% of the over 33 t category of vehicles is accounted for by only 3 sectors (food, groupage, and agriculture). These relatively large fleets, however, still represent only a small proportion of the total heavy vehicle fleet suggesting there are many small operators in the UK which combine to represent a large proportion of total freight movements. This 'long tail' is an important constituency within the heavy freight picture. An analysis of warehouse facilities (the biggest constituent of supply chain nodes) is shown in Figure 3.3. This shows that the national warehouse estate is dominated by the 3PL's plus the retail and food sectors.

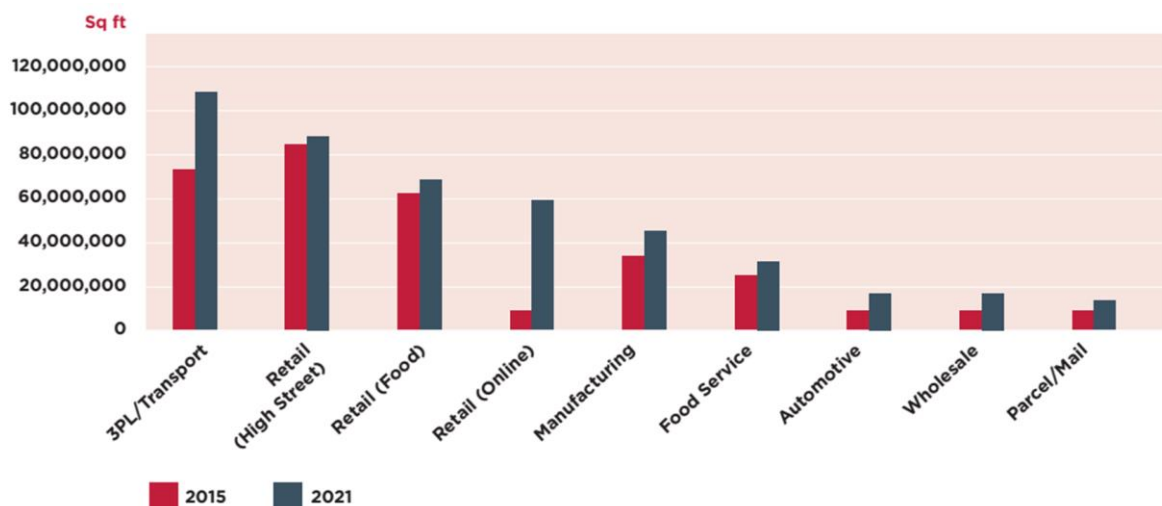


Figure 3.3: UK Warehouse sizes by sector.

3.3 Journey Analysis Using Agent-Based Techniques

Journeys are characterised by journey ‘legs’. A Journey will have at least one leg and probably multiple legs. A journey leg is a discrete origin and destination pair. The journey will be a fundamental consideration in determining the preferred ERS topography and battery capacity for the vehicle.

To specify the full ERS system (OLE topography, static battery charging network, and vehicle battery capacity) it is necessary to understand the following:

- For an operator: to identify the most challenging journey experienced by any lorry in a year so that a sufficient battery capacity can be specified for all anticipated journeys
- For the infrastructure provider: to consider all likely journeys within the country so that the proposed system design can be future-proofed as far as possible

This section summarises the journey analysis which was used to support the specification of vehicle battery sizes and ERS/static charger network topographies which are described in Chapters 4, 5 and 6. An ‘agent-based’ approach was adopted. (Additional details and assumptions are provided in Appendix B). Origins and destinations can be characterised by their function as nodes within the supply chain diagram. Supply chain nodes include factories, warehouses, ports, railheads, stores and sources of raw materials such as forestry and quarries. Journeys can therefore be characterised as ‘port to warehouse’ or ‘warehouse to store’, etc.

From a knowledge of the location of all logistics nodes, it is possible to generate a ‘fully dense’ set of all possible journeys which connect all possible origins to all possible destinations. This fully dense set of journeys can be incorporated into agent-based computer simulation models to explore how different mixes of charging networks, ERS topographies and battery sizes impact the logistics operations. Important in this analysis is the fact that logistics nodes can, and often do, change ownership or function or sector. Consequently, journeys that may not be likely now may become practical in future. The ‘fully dense’ analysis covers all such possibilities.

This fully dense set of journeys, however, is only a partial description of the logistics activity. Journeys are often linked together over the course of a working day so that vehicles can be utilised more fully. A classic example of linked journeys is the retail store multi-drop delivery. Store multi-drops present a challenge to the ERS concept because retail stores are not as likely to be located close to the ERS as warehouses. In fact, some of the more challenging store multi-drop journeys may not involve any traveling on the ERS. Establishing the best solution requires consideration of four different charging scenarios and three different journey types.

3.3.1 ERS with no Static Charging

The pure ERS solution offers the possibility of road freight operations not requiring any off-ERS charging. In this scenario, the combination of batteries and ERS is sufficient to complete all anticipated journeys. This will be possible for a proportion of the total vehicle population that travels warehouse-to-warehouse entirely along the ERS network. It is particularly attractive because no warehouse charging would be needed in many situations. Consequently, it is worth exploring and will provide some valuable insights into battery sizes and the need for charging.

3.3.2 ERS with Wayside ‘Public Realm’ Static Charging

Combining the ERS with a static charger network provides an infrastructure that should be more robust and efficient because it allows journeys to incorporate significant off-ERS legs. This will be necessary for journeys in which vehicles need to travel long distances off the ERS network.

3.3.3 ERS with Destination Charging (no Wayside Static Charging):

This allows the vehicle to charge at the destination without any time penalty (i.e. whilst unloading/loading). This is the most attractive static charging option, but it may not always be available (depending on the nature and ownership of the destination site).

3.3.4 ERS with Destination Charging, and Wayside Static Charging

In some circumstances, operators might want to reinforce the existing ERS plus static charger network with chargers at logistics origins/destinations where they can take advantage of the loading/unloading time to charge the vehicle (thus avoiding the potential need to include additional stops in the journey plan to charge at static chargers enroute). This configuration offers the greatest operational flexibility for the fleet operators, but they may not always have sufficient control over the destination sites to mandate the installation of the destination charging infrastructure.

3.3.5 Journey Types

Three different journey types have been considered:

- Warehouse-to-Warehouse
- Multi-Drop
- Tramping

Of these, multi-drop journeys represent the most difficult journeys to service because they always include multiple legs with a high fraction of off-ERS activity.

A comprehensive consideration of all logistics scenarios is not possible but, as in the previous studies reported in WP2, the work reported here identifies several ‘corner cases’ within each journey type that can be used to define the performance envelope of the system.

Warehouse to Warehouse (WTW)

The first journey type is that of the warehouse-to-warehouse (WTW) operation where vehicles travel from one supply chain node to another without any intermediate stops. Some of the corner cases within this family of journey types present a big challenge as the journeys are generally long distance and not all warehouses are well connected to the strategic road network. This results in large energy requirements combined with long sections of off-ERS movement.

WP2 considered the energy requirements of these journeys assuming they were routed using the current technology (i.e. quickest route). WP4 extends this work to consider how the energy needs could be modified if the routes prioritise travel on the ERS to minimise battery size. In this consideration it is also necessary to take account of any potential increase in the journey time. (Increasing journey times ultimately translates into increasing fleet sizes as the vehicles complete less journeys in each period).

Store Multidrop

Store multi-drop operations comprise journeys which involve multiple drops within a single working day. The journeys usually begin, and end, in the same overnight depot. WP2 considered the battery size required to meet the store multidrop journeys with and without the ERS. WP4 has extended this work to consider the implications of wayside charging and destination charging (at store) in addition to the ERS.

Tramping

This journey type represents a more extreme version of the store multi-drop journey. It typically involves multi-day journeys which cover long distances and multiple drops/pick-ups. This journey type comprises long sections of on-ERS operation plus long sections of off-ERS operation plus one or more overnight layovers at public realm truck-stops. Such journeys are commonplace and are typically operated by a large number of small companies.

3.3.6 Summary of Results

A selection of results from the agent-based analyses is summarised in Table 3.2. It can be seen that the most robust solution (least disruption to existing operations) involves a combination of ERS and destination charging. This solution, however, may not be available to all operators. ERS plus wayside charging can be seen to be a viable alternative, resulting in a system which is accessible to all operators with only minor (and acceptable) disruption to existing operations. In the table below, ERS 'Light' refers to the ERS network described in Chapter 5 which is subsequently selected as the basis for the 'Preferred System' (5,500 single-track-km).

Scenario Used	Case	Extra time required as % of diesel journey	Worst time penalty for any journey	Battery size (kWh)	% Journeys Needing >500 kWh	Comment
No ERS, no wayside charging, no destination charging	Warehouse to warehouse	N/A – experiment to establish max battery size requirement	N/A	1,167	65%	This experiment was to establish the size of battery required to cover 95% of all possible warehouse-warehouse journeys without any intermediate re-charging
ERS and destination charging	Store Multi Drop	N/A – experiment to find the smallest battery that could do all multi-drop journeys with ERS + Destination charging	N/A	500	0	This experiment established that all multidrop journeys were possible using a 500 kWh battery with destination charging and ERS light
ERS only	Store Multi Drop	N/A – time to complete journeys was not considered	N/A	600	13.1%	This experiment shows that a 600 kWh battery with the ERS could complete 95% of all multidrop journeys but no information was generated with regard to overall fleet working time
Destination charging only	Store Multi Drop	N/A – time to complete journeys was not considered	N/A	685	10 %	This experiment showed that a 685 kWh battery with Destination charging only could complete 95% of all journeys but no information was generated with regard to overall fleet working time
Wayside charging only	Store Multi Drop	7.4%	55%	500	0	This experiment showed wayside charging only resulted in a 7.4% increase in overall fleet time and the worst journey took 55% longer
Wayside and destination charging	Store Multi Drop	1.34 %	33%	500	0	This experiment showed that wayside and destination charging resulted in a 1.34% increase in overall fleet time and the worst journey took 33% longer
ERS and wayside charging	Store Multi Drop	0.47%	14.9%	500	0	This experiment showed that wayside charging plus ERS resulted in only 0.47% increase in overall fleet time and the worst journey took 15% longer
ERS and destination charging	Store Multi Drop	0.0%	0%	500	0	No increase in fleet time
Everything	Store Multi Drop	0.0%	0%	500	0	No increase in fleet time

Table 3.2: Summary of results for agent-based analysis.

The full analysis showed that:

- all existing logistics operations in the UK could be performed by electric vehicles on an ERS system comprising 5,500 STK's supplemented by a public network of wayside static charging sites provided all of the large HGVs had 500 kWh batteries.
- Approximately 55% of HGVs are employed in transporting commodities between warehouses. Of these warehouse-to-warehouse journeys, 87% of the journeys could be completed by vehicles with batteries of less than 500 kWh, 77% less than 300 kWh batteries and 60% less than 150 kWh batteries. The vehicles with smaller batteries would be significantly lighter and lower cost than vehicles with 500 kWh batteries. Consequently, some fleet operators could make significant cost savings if they divided their fleets in two: (i) vehicles that specialised in WTW journeys on the ERS; and (ii) more flexible vehicles that could do multidrop journeys off the ERS network.

3.4 Fleet Flexibility

A vehicle with a small battery might be lighter and cheaper than its bigger battery counterpart, but it would be constrained to a smaller set of journey types. Some operators have suggested that the tighter planning constraints introduced by smaller batteries would require a larger fleet to compensate for this new operational planning constraint. The permutations of battery size, journey type, and number of vehicles required in the fleet are too numerous to be thoroughly explored here. Addressing these possibilities represents a case for further study, but some general observations can nevertheless be made about fleet flexibility and the desirability, or otherwise, for a single type of vehicle to be capable of servicing all journeys. To address this question, it is useful to explore a 'year in the life of a lorry'.

3PL operations represent a large proportion of the UK fleet activity, and these operators leverage vehicle flexibility to transfer assets across different contracts. A 3PL operation has therefore been examined and the analysis shown in Figure 3.4 below summarises a year in the life of their fleet. The fleet comprises 189 vehicles and those vehicles visited 1,923 places during the year. The diagram shows that half of the vehicles in the fleet visited 800 or more of the destinations during the year and only a very small fraction of the fleet was assigned to a small sub-set of routes (i.e. repeated journeys)

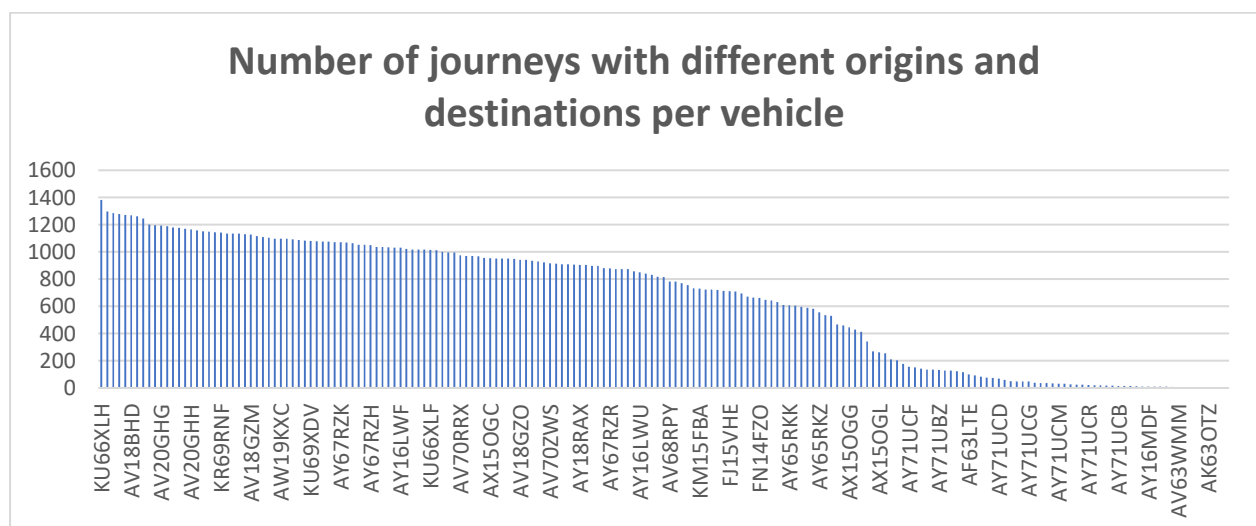


Figure 3.4: Number of destinations visited by each vehicle in a 3PL fleet of 189 vehicles.

It is not clear whether fleet operators would opt to use vehicles with smaller batteries at the expense of introducing more complex logistics arrangements, or whether they would opt for a fleet of more flexible but more expensive vehicles. This choice will depend on many factors which cannot be predicted at this stage. The analysis to date assumes that all vehicles in each operator fleet will be specified against the most demanding journeys which need to be serviced by that fleet. The results suggest that an installed battery capacity of 500 kWh, with 80% usable charge, will meet this requirement.

3.5 Conclusions

It is concluded that ERS-enabled electric vehicles equipped with a 500 kWh battery would be able to use the ERS 'Light' network in combination with wayside static chargers and perform with all the operational flexibility of diesel vehicles if deployed within today's logistical environment. Vehicles with smaller batteries may also be appropriate for an important sub-set of operations but the detailed possibilities have not been pursued here. The extent to which vehicles with different battery sizes might provide a more attractive business solutions for different vehicle fleet operators is an important area for more detailed study.

4. The Vehicle Fleet Operators' Perspective

In this chapter, the challenge of moving to zero-emissions operations is examined from the Vehicle Fleet Operators' (VFO's) point-of-view. Based on projections for the prices of different zero-emission vehicles, the Total Cost of Ownership is calculated at different points in time over the period 2025-2050. The chapter finishes with some 'Case Study' examples illustrating different future scenarios.

The rate of market take-up for zero emission vehicles will be dictated by a combination of government legislation and the commercial case for the VFO's to retire their conventional diesel fleets and replace them with the new vehicles. An important component of the national electrification strategy, therefore, will be to make fleet renewal commercially attractive to these operators.

The Total Cost of Ownership (TCO) is the key commercial metric but, before exploring this metric, it is vitally important to recognise that the reliability of the new technology and confidence in the vehicle suppliers to provide product warranties and after-sales support are essential pre-requisites for change. There must be a prevailing atmosphere of confidence if a swift transformation is to be achieved.

In the following sections, the TCO is examined through the eyes of the VFO for a range of different vehicles which are capable of operating across the spectrum of journey-types described in the previous chapter. The TCOs for three different routes to zero emissions are calculated:

- ERS-enabled Battery Electric Vehicles (ERS-BEV).
- 'Big Battery' Electric Vehicles with no need for a supporting ERS (BB-EV).
- Hydrogen Fuel Cell Electric Vehicles (HFC-EV).

A fourth possibility is bio-fuels, but this option is not included in this study for the reasons explained in Chapter 2.

4.1 The Route to Zero Emissions

The event which triggers the switch to zero emission vehicles will most likely be some form of government legislation or government 'encouragement' (e.g. bans on diesel powertrains, or the introduction of vehicle scrappage schemes). The switch, when it comes, will be made easier when the cost of operation becomes less than the cost of diesel operations. At that point, the VFO's will have choices to make when deciding how best to switch their fleet. ERS will become the preferred system only if the total cost of ownership is seen to be lower than that of the credible alternatives (e.g. 'Big Battery' or Hydrogen).

The TCO is a measure of the cost to run a fleet considering all aspects of the operation – not only the capital cost of purchasing the vehicles. The TCO costs considered in this study are:

- Vehicle purchase, financing, and depreciation.
- Depot supporting infrastructure (e.g. grid-connected charging equipment, or hydrogen storage tanks).
- Vehicle maintenance (parts and labour).
- Fuel costs.

The cost of drivers, insurance, damage repair, and other sundry items have not been included in the TCO calculation because these numbers are common to all types of vehicle and do not contribute to any differences between them.

4.2 Vehicle Purchase Price

The first step is to calculate the cost of purchasing the vehicles. Diesel technology is mature and the price of diesel vehicles over a long period of time is likely to remain relatively stable. For ERS-BEVs, BB-EVs and HFC-EVs, however, the technology is immature and the purchase prices of these vehicles can be expected to change significantly over the coming years. The projected costs of ERS-BEV, BB-EV, and HFC-EV over the period 2025-2050 have therefore been calculated and compared to the benchmark cost of purchasing a diesel-powered vehicle.

The specifications for the various types of vehicle which have been examined are summarised below.

Diesel 'Baseline' Lorry

- 38 t Gross Combination Weight (GCW), 4x2 tractor
- 300 kW Traction Power

ERS-Enabled BEV Lorry (ERS-BEV)

- 38 t GCW, 4x2 tractor
- Traction Power: 300 kW
- Battery Capacity Options of: 150 kWh, 300 kWh, 500 kWh

'Big Battery' EV Lorry (BB-EV)

- 38 t GCW, 4x2 tractor
- Traction Power: 300 kW
- Battery Capacity: 1,200 kWh

Hydrogen Fuel Cell Electric Vehicle Lorry (HFC-EV)

- 38 t GCW, 4x2 tractor
- Traction Power: 300 kW
- Fuel Cell Power: 150 kW
- Battery Capacity: 150 kWh
- Hydrogen Tank Capacity = 30 kg H₂ at 350 bar

4.2.1 Vehicle Price Trajectories

The baseline diesel lorry currently has a purchase price of around £78,000 (Blakemore 2018, adjusted for inflation). It has been assumed that this price will remain constant over the period 2025 – 2050 because diesel lorry technologies are mature/stable. The diesel lorry price is subdivided as follows:

- Rolling chassis + cab (incl. driven axle): £38,000.
- Powertrain, PAS, compressors, and all other hydraulic/air ancillary devices: £40,000.

The future purchase price of the BEVs and HFC-EVs has been calculated by taking a bottom-up approach, starting with the rolling chassis and cab cost for a diesel lorry and adding the costs of the relevant additional components. It is assumed that BEV/HFC lorry powertrain technologies will reduce in cost over the period of interest, reflecting the component price trends presented in Table 4.1.

Component	2021	2030	2040
Battery Pack Price [£/kWh]: includes cells, packaging, thermal control equipment, condition monitoring sensors, etc.	250	77	50
EV Driveline Price [£/kW]: includes motors, inverters, controllers, pantograph, and all electric-powered ancillary units (compressors, PAS, etc)	350	139	75
Hydrogen Fuel Cell [£/kW]	800	246	160
Hydrogen Fuel Tanks [£/kgH₂]	1,000	307	200
Rolling Chassis and Cab (incl. driven axle) [£]	38,000	38,000	38,000
Production Cost Multiplier: accounts for the effect of low volume production during the early years.	x1.5	x1.1	x1.0

Table 4.1: Cost projections for various vehicle components (source: authors).

4.2.2 Vehicle Future Price Comparisons

Using the price trends defined in Table 4.1, the projected purchase price curves of the various lorries has been calculated and the results are presented in Figure 4.1.

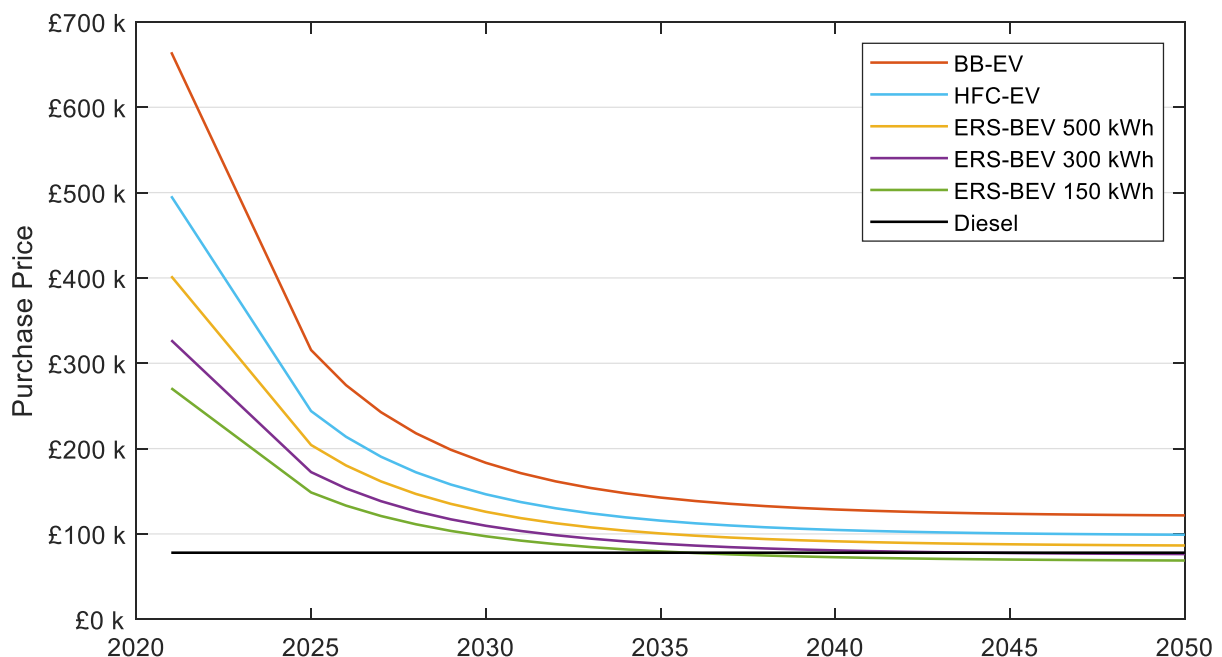


Figure 4.1: Lorry purchase prices over the period 2021-2050.

4.2.3 Annualised Costs

It is common practice for large HGV fleet operators to purchase new vehicles and then run them for a fixed period of time before selling them into the second-hand market. This is termed the vehicle 'First Life' and the second-hand value of the vehicle must be accounted for in the calculation of TCO. The first life of the tractor units has been assumed to be 6 years, which is typical of the industry. It has also been assumed that, once the market matures, all types of vehicle depreciate at a rate of 30% per annum, consistent with current diesel trends, leaving a residual value of ~17% at the end of the vehicle first life. All vehicles are assumed to be purchased with a commercial loan over 6 years at 4% interest p.a.

4.4 Depot Infrastructure Costs

Depending on the choice of vehicle, the operator will need to install the appropriate supporting infrastructure in the overnight depot. This will comprise battery charging equipment for BEV's and hydrogen storage/dispensing equipment for HFCs.

The size/capacity of the infrastructure will be dependent on the size of the vehicle fleet. In the following calculations, a fleet size of 100 vehicles has been assumed.

4.4.1 ERS-BEVs

Three battery configurations have been considered for the ERS-BEV class of vehicle with on-board battery sizes of 150 kWh, 300 kWh, and 500 kWh. The following assessment uses the intermediate vehicle (300 kWh) as an example; similar calculations would apply for the other vehicle configurations.

It has been assumed that all 100 vehicles return to the depot for overnight charging at the end of each working day, and that they remain there for an undisturbed period of 8 hours whilst plugged-in to the charging devices. Based on these assumptions (for further detail see Appendix F):

- Charging Infrastructure = 100 x 50 kW charging units at £20,000 per unit (installed cost).
- Aggregated grid connection requirement = 4 MW (assumes load balancing across the system which compensates for different battery states-of-charge on different vehicles).
- Grid connection cost = £3Mn (assumes an HV connection to local district network with significant cable-runs between the depot and the point of grid connection).

The prices for chargers and grid connection costs are assumed to remain relatively stable in future. This reflects the maturity of the market for these items. (Electric chargers in the range 100-150kW are already commonplace). The life of the charger units has been assumed to be 10 years based on estimated life profiles for frequently used light industrial equipment. It has been assumed that the infrastructure purchase and installation costs have been funded by a commercial loan at 4% interest over the 10-year lifetime of the equipment.

4.4.2 BB-EVs

Each BB-EV is assumed to have a battery capacity of 1,200 kWh. This is considered to represent a 'reasonable median' for UK operations and is based on a daily range requirement of around 500 km. (This is more than the average daily figure of 372 km, but the battery capacity needs to accommodate the longest daily range requirement). It has been assumed that all 100 vehicles return to the depot for overnight charging at the end of each working day, and that they remain there for an undisturbed period of 8 hours whilst plugged-in to the charging devices. Based on these assumptions:

- Charging Infrastructure = 100 x 150 kW units, costing £50,000 each (installed price)
- Aggregated grid connection requirement = 10 MW (assumes load balancing across the system which compensates for different battery states-of-charge on different vehicles).
- Grid connection cost = £4Mn (assumes an HV connection to local district network with significant cable-runs between the depot and the point of grid connection).

The assumptions about infrastructure life and loan interest rates are the same as those described for ERS-BEV's.

4.4.3 HFC-EVs

It is assumed that the operator installs hydrogen tanks and dispensers at the depot which are supplied by regular tube-tanker deliveries of green hydrogen generated by a third-party supplier at a remote site using alkaline electrolyzers. The cost of installing the depot-based storage and dispensing facilities can be expected to reduce significantly over time as hydrogen technologies mature and this reducing cost profile has been allowed for (see Appendix D for a more detailed discussion).

The depot hydrogen infrastructure life has been set at 20 years on the basis that the tanks and dispensers are likely to be robust and well protected by barriers etc and manufacturing quality is underpinned by well-established chemical engineering practices. The purchase is assumed to be funded by a commercial loan at 4% interest over the 20-year lifetime of the equipment.

Note: *Since HFC-EVs have an on-board battery, there may need to be some depot-based battery charging infrastructure in addition to the hydrogen infrastructure. This has not been included in the analysis.*

4.5 Maintenance Costs

The maintenance costs, shown in Table 4.2, comprise the cost of replacement parts and consumables plus the cost of staff. It has been assumed that the annual maintenance cost for an electric lorry is 90% of the maintenance cost for a comparable diesel lorry. This reflects the simplicity of the electric powertrain (compared to diesel), plus the reduction in use of consumable items (filters, lubricants, etc). No reduction has been made for hydrogen vehicles owing to the added complexity of maintaining the on-board tankage, fuel cell and pipework for the hydrogen gas.

	Diesel	ERS-BEV	BB-EV	HFC-EV
Parts	£5,000	£4,500	£4,500	£5,000
Labour	£15,000	£13,500	£13,500	£15,000

Table 4.2: Annual maintenance costs per vehicle type (source: authors).

4.6 Fuel Costs

For the purposes of making fuel price comparisons between diesel vehicles, BEV's and HFCV's, some important simplifying assumptions have been made. The consumer prices of diesel and grid-distributed electricity have been assumed to remain relatively stable over the period 2025-2050 (neglecting general inflation and extreme events). This is because these activities are currently based on mature technologies and, in future, it is assumed that the price of renewable electricity will decline to match the current price of gas-powered generation.

Based on these assumptions, the retail price of diesel for fleet operators, excluding VAT, has been assumed to remain constant over the period 2025 – 2050 at £0.96 per litre. The price of electricity has been assumed to remain constant over the same period at 5 p/kWh (wholesale generation price) and 12 p/kWh (bulk user retail price). The bulk user retail price assumes that fleet operators will negotiate bulk purchase agreements with their electricity suppliers at a slight discount to the regular domestic price of electricity. For comparison, Network Rail purchased traction electricity from a commercial electricity supplier at around 10 p/kWh in 2017 (Network Rail 2017).

For BEVs, it is assumed that vehicle fleet operators will purchase electricity at their bulk user retail price when charging vehicles overnight in their depots, but will pay a premium price when purchasing electricity from the ERS, or from static chargers, during the working day. This premium provides the source of income which is required to cover the capital and operating costs of the system developer/operator and provide a reasonable profit.

The price of green hydrogen delivered to the depot can be expected to vary significantly over the period 2025 – 2050 as a result of technology advances and increasing volumes of production. This effect has been allowed for as described in Appendix D.

For hydrogen-powered vehicles, the calculated prices for hydrogen (grey and blue versions, as well as green) are presented in the figure below. The decline in green hydrogen prices over time is not as sharp as might be expected. This is because the price of producing green hydrogen by electrolysis is dominated by the price of electricity which, as explained above, remains fairly stable. Grey and blue hydrogen prices remain fairly stable because they both rely on gas reformation technologies which are quite mature.

Two price curves for green hydrogen are shown in Figure 4.2 because the electrolysis process might be powered in two different ways. It might be supplied with electricity taken from a 'standard' grid connection (bulk user purchase price = 12 p/kWh) or it might be supplied by a 'captive' source of generation which is purpose-built and owned by the hydrogen producer (wholesale generation price = 5 p/kWh). This difference in electricity price is reflected almost directly in the price of hydrogen although, arguably, the use of wind power to produce hydrogen in this way would severely constrain the location of hydrogen production facilities and this might increase the cost of transporting the gas to the points of use around the country. (This additional cost has not been recognised in the calculations reported here). Electricity prices of 5 p/kWh and 12 p/kWh have therefore been taken to underpin the upper and lower bound estimates for hydrogen prices in the remainder of this study.

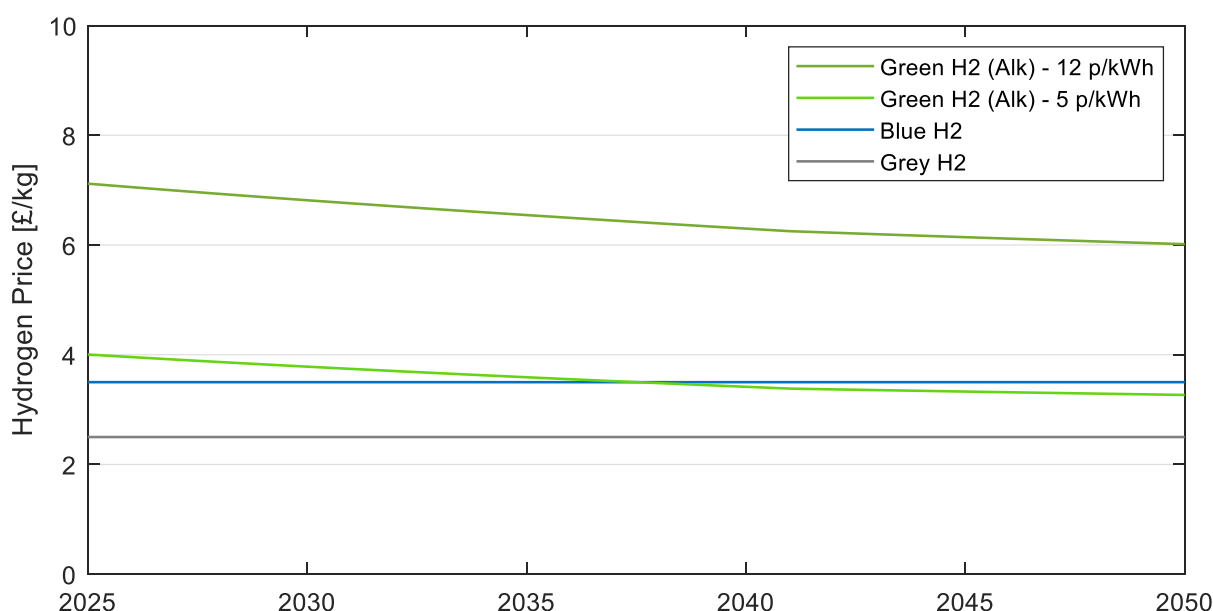


Figure 4.2: The calculated hydrogen fuel prices for the vehicle TCO.

For bulk user electricity prices of 12 p/kWh, the price of green hydrogen delivered to the operators' depot storage tanks has been calculated to be £7.11 per kg H₂ in 2025, reducing to £6.01 per kg H₂ by 2050 (for details, see Appendix D). This price curve has been calculated from the cost of electricity required to power the electrolysis process plus the capital and operating costs of the equipment required to perform the electrolysis, compress/store the gas,

and transport it to the VFO depots. For ‘captive’ renewable electricity at 5 p/kWh, the price of green hydrogen has been calculated to be £4.00 per kg H₂ in 2025, reducing to £3.27 per kg H₂ by 2050.

4.7 Estimated TCOs for a 6-year ‘First Life’

A summary of the final TCO estimates for various years between 2025 and 2050, along with their diesel fleet comparators, is presented for BEV options in Table 4.3 and for HFC-EV options in Table 4.4. The cells coloured green indicate where it is *cheaper* to operate a BEV lorry than to operate the comparable diesel lorry.

In the tables it has been assumed that, for all the BEV options, electricity is purchased at a flat rate of 12 p/kWh. This simplifies the presentation of the data but it should be noted that, in reality, the lorry operators will purchase electricity in varying proportions from different sources at different prices (e.g. ‘at the wires’ on an ERS system or at publicly-accessible wayside static charging points).

Year	Diesel	ERS-BEV (150 kWh)	ERS-BEV (300 kWh)	ERS-BEV (500 kWh)	BB-EV (1,200 kWh)
2025	£392,023	£411,636	£446,729	£487,921	£611,092
2030	£392,023	£358,647	£381,836	£407,154	£474,768
2035	£392,023	£340,345	£360,143	£380,940	£432,731
2040	£392,023	£333,336	£352,078	£371,467	£418,329
2045	£392,023	£330,510	£348,912	£367,848	£413,122
2050	£392,023	£329,339	£347,630	£366,418	£411,175

Table 4.3: The estimated diesel and BEV fleet TCO over 6 years at different years.

Year	Diesel	HFC-EV (Grey H ₂)	HFC-EV (Blue H ₂)	HFC-EV (Green H ₂ , Electrolysis @ 5 p/kWh)	HFC-EV (Green H ₂ , Electrolysis @ 12 p/kWh)
2025	£392,023	£562,423	£625,588	£657,438	£854,110
2030	£392,023	£457,525	£520,691	£538,562	£730,126
2035	£392,023	£423,127	£486,293	£491,952	£678,667
2040	£392,023	£410,398	£473,564	£468,241	£650,345
2045	£392,023	£405,329	£468,495	£457,686	£635,402
2050	£392,023	£403,193	£466,359	£451,664	£625,198

Table 4.4: The estimated diesel and HFC-EV fleet TCO over 6 years at different years.

From Tables 4.3 and 4.4, the following conclusions can be drawn.

- (i) Only the ERS-enabled BEV solutions are likely to meet or beat the diesel benchmark costs before 2050. This crossover is likely to be achieved between 2027 and 2033 depending on the vehicle's on-board battery capacity.
- (ii) BB-EV is significantly more expensive to operate than the ERS-BEV lorries.
- (iii) Hydrogen is the least attractive option by a wide margin. This is because of the high purchase price of the HFC-EV (Figure 4.1) and the high price of green hydrogen (Figure 4.2).

The low TCO's for diesel operations means that some form of Government intervention will be required to force lorry operators to switch away from diesel to the new zero emissions vehicles in future. This might be by mandate, or by sponsoring an ERS system which enables the TCO for electric vehicles to meet, or beat, the diesel benchmark.

4.8 Fuel Pricing

From Table 4.3 it can be seen that, in the presence of an ERS system, the TCO for electric vehicles quickly becomes competitive with, and then cheaper than, diesel vehicles. This means it would be possible to place some measure of tax on the electricity used for freight transport as the years pass by, without making the TCO for ERS-enabled electric vehicles any higher than that for diesel vehicles. This tax headroom is shown in Figure 4.3 where the margin between 12 p/kWh and that electricity price required to maintain parity with diesel TCO's is shown for various different battery sizes, including BB-EV. Negative numbers indicate tax headroom; positive numbers indicate a need for subsidy. After 2035, the headroom for ERS-enabled vehicles levels out to a stable margin of around 5 p/kWh. The Big Battery vehicle never achieves this position, always requiring a government subsidy because of its higher initial purchase price.

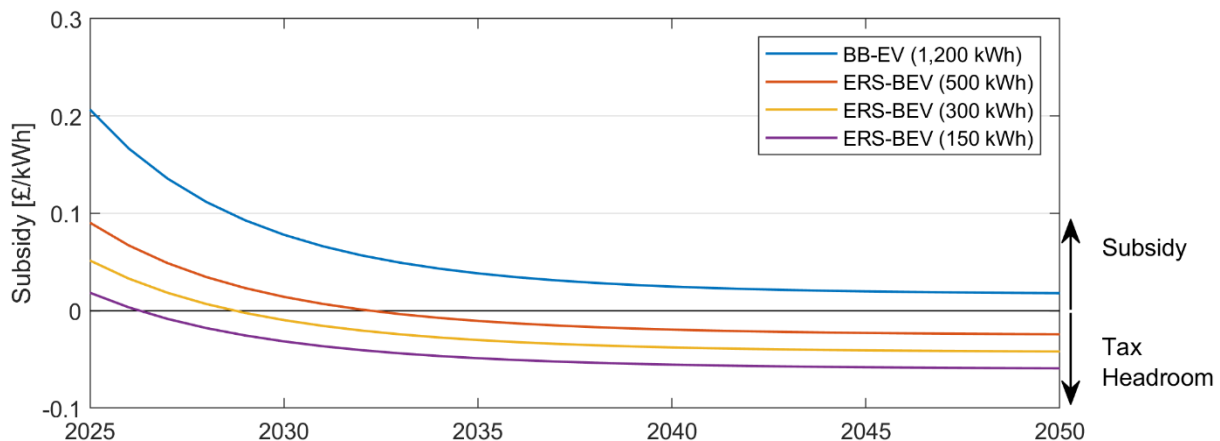


Figure 4.3: The electricity fuel subsidy for the different BEV configurations (negative values provide headroom for tax revenue generation).

Using the same logic, if the government were to adjust the fuel price of hydrogen to match the diesel benchmark, a substantial subsidy would always need to be provided at the point of purchase. The value of this subsidy (£/kg H₂) is shown in Figure 4.4.

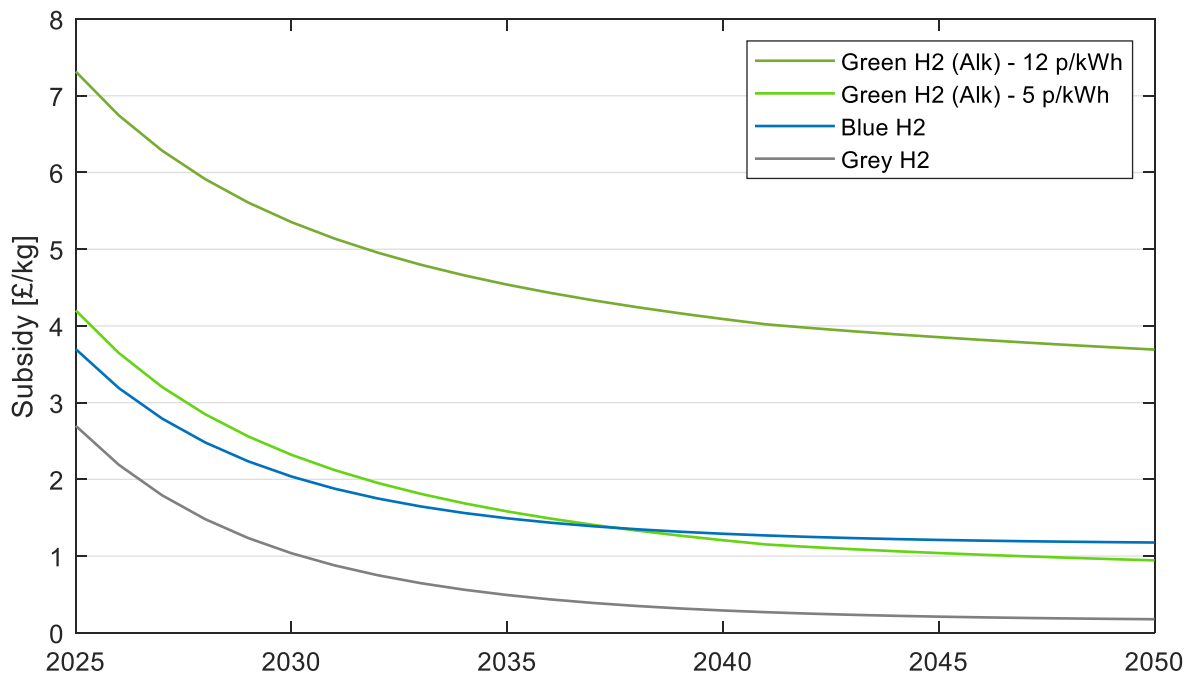


Figure 4.4: The fuel subsidy required to meet TCO parity with the diesel comparator for the various forms of hydrogen.

To explore the implications of the TCO's and fuel prices outlined above, it is helpful to examine a small number of specific case studies. These are presented in Sections 4.9 and 4.10 below.

4.9 Case Study: ERS-BEV or HFC-BEV?

The most obvious question for the VFO is “should we go electric or hydrogen?” This case study examines the choice between ERS-BEV and HFC-BEV in the context of a specific scenario, namely:

- Evaluation Year: 2035
- Fleet size: 100 vehicles
- Average annual vehicle mileage: 93,000 km
- Vehicle battery size: 300 kWh
- Average energy consumption: 1.9kWh/km

For a vehicle driving 93,000 km per annum over a 5-day working week, the daily driving distance is approximately 370 km. If this vehicle has a medium-size battery (300 kWh), the range associated with a full battery charge will be around 120 - 150 km. It will therefore be necessary to purchase the balance of electricity required to complete 370 km either from the ERS system (the wires) or from the static charging network. In this case, the balance will need to be sufficient to provide an additional range of 220-250 km each day. This represents roughly 66% of the traction electricity used by the VFO.

The business case studies reported in Chapter 6 consider two different scenarios. The first is the ‘Government Intervention’ scenario, in which the government chooses to subsidise the price of electricity/hydrogen in order to maintain the current cost-base of the transport industry. The second is the ‘Free Market’ scenario, in which the government takes no position on the price of operations and leaves it to the free market to select the preferred solutions.

The cost of operations to the VFO are examined under these two scenarios in the following sections.

4.9.1 The Government Intervention Scenario

In this scenario, the cost of operating a fleet of ERS-BEV, BB-EV, or HFC-EV's is constrained (by definition) to be equal to the cost of operating the benchmark diesel fleet. This makes the decision to change much easier for the VFO and the choice of technology would most likely be based on the availability of suitable supporting infrastructure at the time of purchase.

4.9.2 The Free Market Scenario

In this scenario, the VFO would make the technology choice based primarily on the cost of operation at the free market prices for electricity and hydrogen. Figure 4.5 shows how this choice could play out.

In this example, for a battery size of 300 kWh and for 66% of all daily electricity purchased at the wires (for simplicity, we neglect the possibility of using wayside static charging sites or 'destination chargers' at captive drop-off locations), the VFO would choose the ERS-BEV solution over hydrogen for electricity prices 'at the wire' of anything up to:

- 25 p/kWh (i.e. 12 p/kWh bulk retail price of electricity paid by the ERS operator plus 13 p/kWh 'wires margin') before the cost of the ERS solution exceeds the cost of hydrogen when purchased from the provider at £3/kgH₂ (considered here to be a sensible lowest bound for the price of green hydrogen as delivered to a VFO in 2035). or
- 61 p/kWh before the cost of the ERS solution exceeds the cost of the hydrogen when purchased from the provider at £7/kgH₂ (considered here to be a sensible median projection for the VFO price of green hydrogen at 2035).

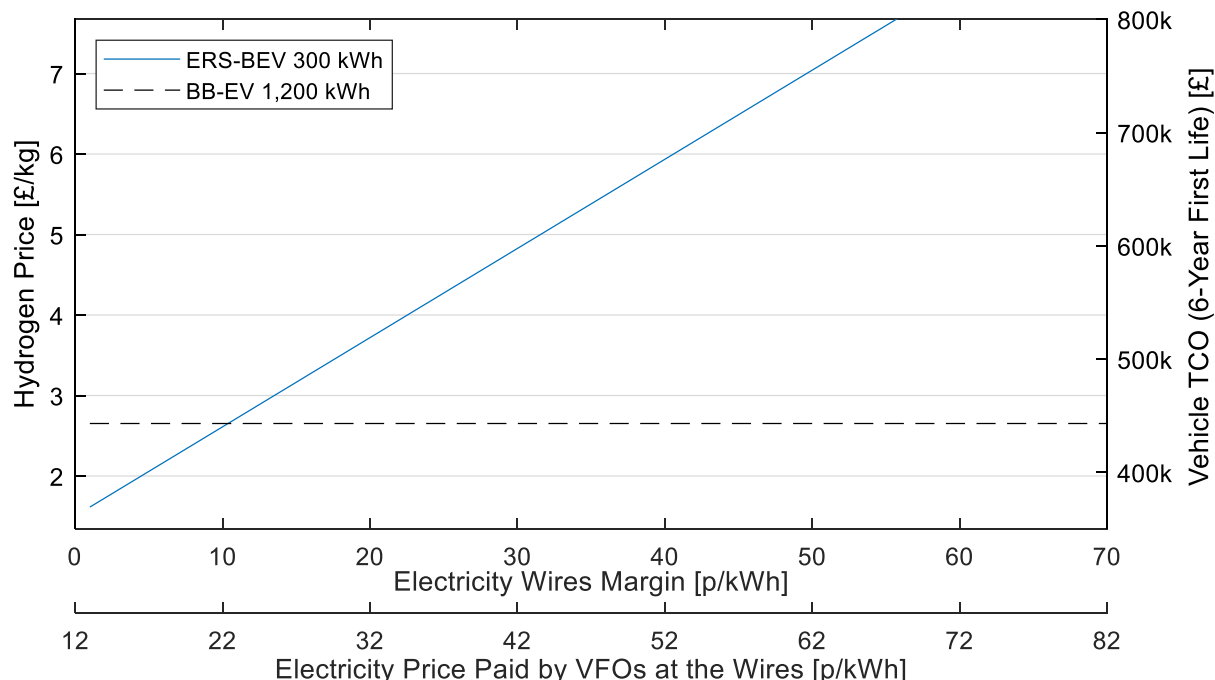


Figure 4.5: Price of Hydrogen (£/kg) versus electricity price/margin chargeable at the wires for ERS-BEV (300 kWh) in 2035.

4.10 Case Study: Daimler Hydrogen Lorry

Daimler recently announced a HFC-EV with the specifications listed below. This vehicle provides a useful comparator for the hypothetical vehicle assumed earlier in this chapter.

- 40 t GCW, 4x2 tractor
- 660 kW Traction Power
- 2x150 kW HFCs = 300 kW
- 70 kWh Battery
- Hydrogen Tank Capacity (40x2) = 80 kg of liquid hydrogen at 700bar

Using the component cost trajectory data presented in the previous section, the cost trajectory for the complete vehicle has been calculated and is shown in Figure 4.6 below.

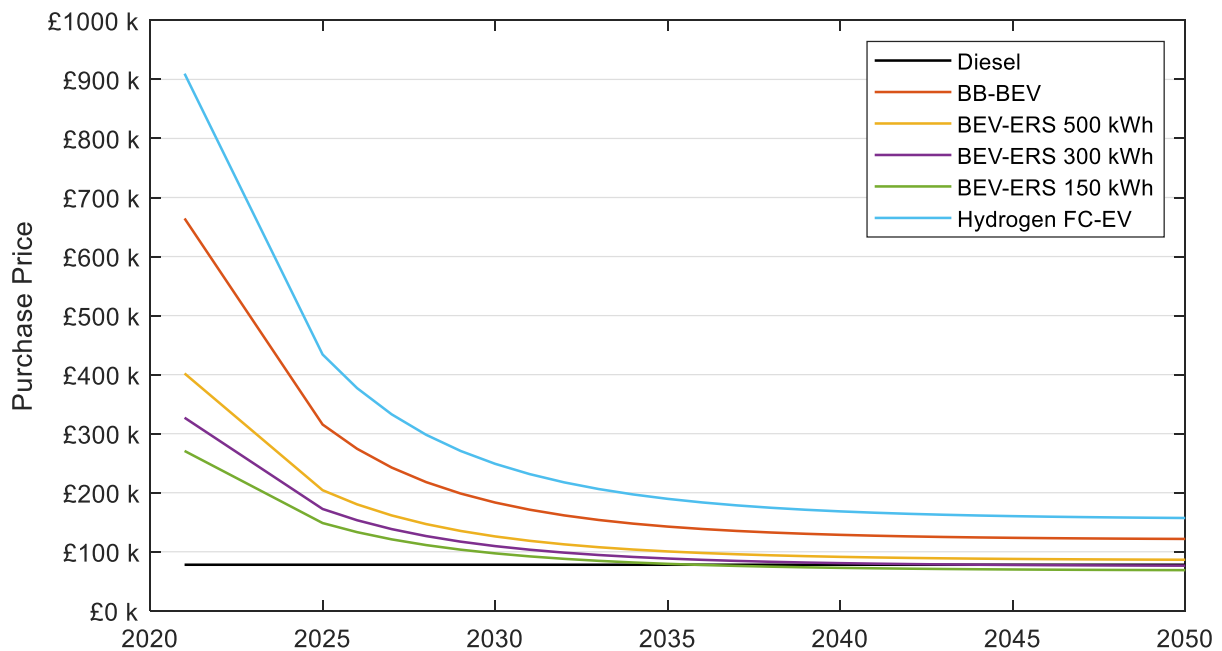


Figure 4.6: Diesel, BEV, and Daimler HFC-EV purchase prices from 2021-2050.

Figure 4.6 shows that the Daimler vehicle would be the most expensive of all vehicle types. The significantly higher purchase price is due to the greater traction power available and the increased hydrogen storage capacity. Based on these projections, the TCO's for the Daimler lorry are shown in Table 4.5 below. They are much less attractive than the figures calculated for the hypothetical hydrogen vehicle. This finding provides some comfort that the hydrogen benchmarks used in this study are not unreasonably weighted against hydrogen technology.

Year	Diesel	Daimler HFC-EV (Grey Hydrogen)	Daimler HFC-EV (Blue Hydrogen)	Daimler HFC-EV (Electrolysis @ 5 p/kWh)	Daimler HFC-EV (Electrolysis @ 12 p/kWh)
2025	£392,023	£752,585	£815,750	£847,600	£1,044,270
2030	£392,023	£557,244	£620,409	£638,281	£829,845
2035	£392,023	£493,512	£556,677	£562,337	£749,051
2040	£392,023	£470,110	£533,276	£527,953	£710,057
2045	£392,023	£460,926	£524,092	£513,283	£690,999
2050	£392,023	£457,149	£520,314	£505,620	£679,154

Table 4.5: The estimated TCO of the Daimler HFC-EV for different hydrogen fuels with the diesel comparator

Given the higher vehicle purchase price, the consequent subsidies required for the Daimler FC-EV to meet parity with the diesel fleet would be also be considerably higher than was the case for the hypothetical HFC-EV, as shown below in Figure 4.7.

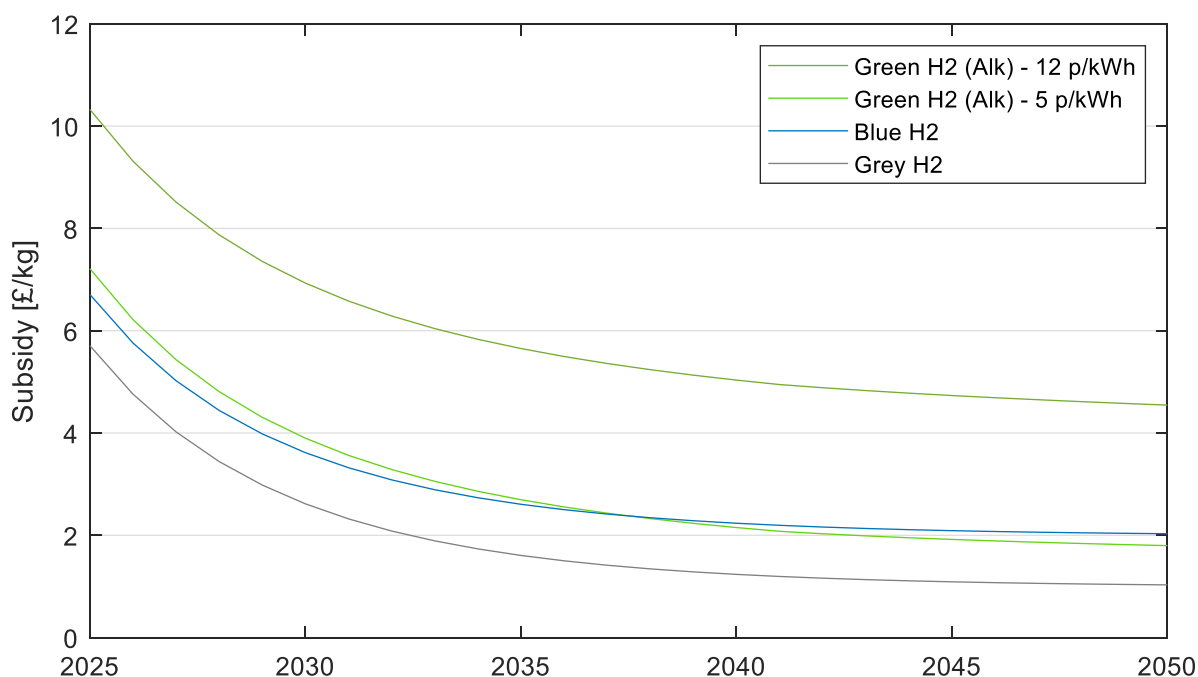


Figure 4.7: The hydrogen fuel subsidies required for the Daimler HFC-EV to reach parity with a diesel vehicle.

5. The National EV Charging Network - System Definition

The performance requirements for the ERS system and its supplementary static charging network are discussed in this chapter. A viable national charging infrastructure must comprise a sufficient length of the ERS ('the wires'), plus a supplementary network of static charging sites which are sufficiently ubiquitous to serve all those vehicles which, at any point in time, might find themselves remote from the ERS and in need of a re-charge. The requirements for designing a system which meets these needs are examined in the following sections.



Figure 5.1: Photograph of the catenary ERS demonstrator in Germany.

5.1 The Catenary ERS Network

Three possible ERS topologies have been examined, each with a different electrified length measured in 'Single Track km' (or STK's). These are illustrated in the diagrams of Figure 5.2 below and are referred to in the following text as the 'Light' (c.5,500STK's), 'Medium' (c.11,000STK's) and 'Heavy' (c.17,000STK's) options.

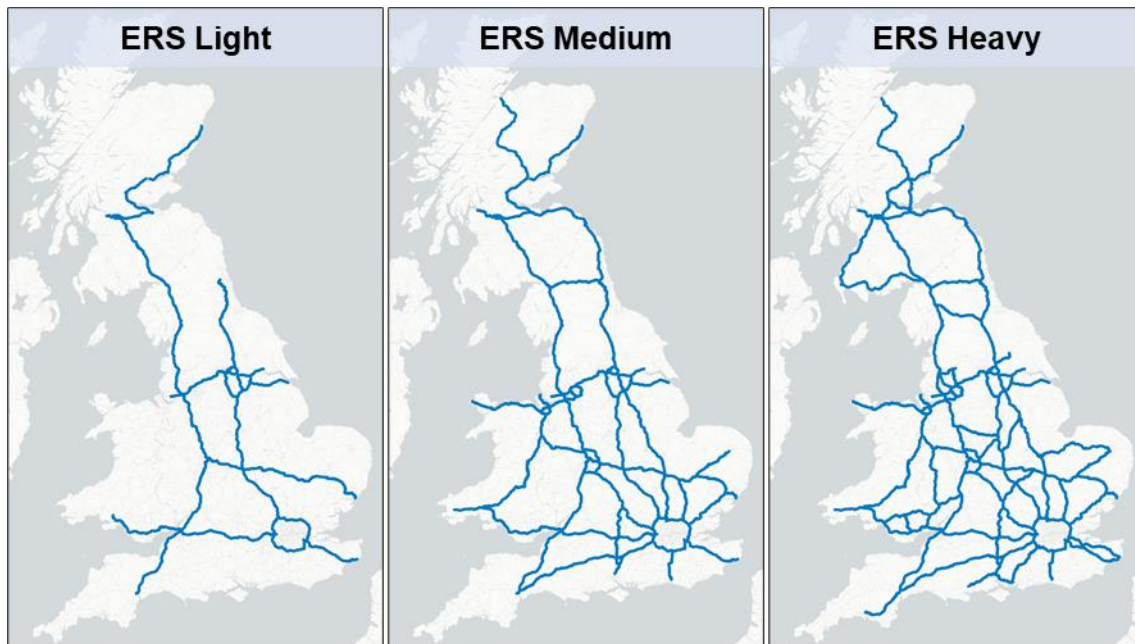


Figure 5.2: Proposed alternative ERS topologies examined in this study from left to right: ‘Light’ (~5,500 STK’s), ‘Medium’ (~11,000 STK’s), and ‘Heavy’ (~17,000 STK’s).

5.1.1. Infrastructure Power Rating

The most important design parameter for the ERS is the target power demand per STK. This figure is determined on any particular stretch of motorway by the number of lorries per km at peak times and the average power demand for each lorry. The average power demand for each lorry is defined by some combination of:

- Traction motor power: assumed to be variable depending on lorry specification with a typical motor power specification of 300 kW.
- Battery re-charging power: assumed to be variable depending on battery size and nature of journey up to a maximum of 300 kW.
- Total demand: subject to an aggregated limit of 300 kW per vehicle (determined by the pantograph capacity).

Based on DfT traffic flow data, an estimate has been made for the number of HGV’s per kilometre at peak times of day on different parts of the motorway network. These HGV densities have then been used to calculate the linear power capacity which is required of the ERS system (MW/STK). Table 5.1 summarises the results. In this table, the peak power demand per lorry is taken to be the aggregated traction/re-charging demand limit (up to 300 kW per lorry). It is assumed that all lorries have an average traction power requirement of 150 kW when running at motorway speed on the flat. It is further assumed that the balance of power available at the pantograph (150kW) will not be drawn by all vehicles simultaneously and, for this reason, a ‘charging diversity factor’ (D) is introduced. This is a multiplier which accounts for the fact that, at any particular location and point in time, the lorries on that stretch of motorway will have different battery re-charging requirements. A rigorous calculation to determine ‘D’ requires a statistical approach that is beyond what has been possible in this study. In the absence of such an analysis, a value of 0.4 has been assigned based on a qualitative review of the logistical studies reported in Chapter 3.

No. of HGVs >25 t per km during Peak Periods of Day	2	3.4 (UK Mean)	6.5	10	14 (UK Peak)
Traction Power [MW/STK]	0.3	0.5	1	1.5	2.1
Battery Recharge Power [MW/STK]	0.3	0.5	1	1.5	2.1
Charging Diversity Factor (D)	0.4	0.4	0.4	0.4	0.4
Total Power Demand [MW/STK]	0.4	0.7	1.4	2.1	3

Table 5.1: ERS linear power capacity (MW/STK) required to support different traffic densities (HGVs per km). Nominal traction power = 150 kW; nominal re-charge power = 150 kW).

Based on this data, the proposed power distribution requirements for a UK national system are summarised in Table 5.2.

Characteristic Parameter	Specification	Rationale
Max Power draw per vehicle	300 kW	Limited by pantograph spec.
Vehicles per lane-km during peak periods (lightly trafficked sections of network)	3	Representative of peak utilisation rates on lightly trafficked stretches of major motorways.
Linear power demand (lightly trafficked sections of network)	0.5 MW per STK	Interpolated from Table 5.1.
Vehicles per km during peak periods (busy sections of network)	8-10	Representative of peak utilisation rates on busy stretches of major motorways.
Peak period linear power demand (busy sections of network)	2 MW per lane-km	Interpolated from Table 5.1.
Max localised vehicle density (10x 20m-long vehicles at 10 m intervals)	10 vehicles per 300 m	Represents the intensity of a cluster of HGV's or a future autonomous convoy (from WP2 report).
Maximum localised linear power demand	3 MW over 300 m per lane	Represents the localised power demands of a cluster of HGV's or a future autonomous convoy.

Table 5.2: Power distribution requirements for a catenary ERS in the UK.

5.1.2 Grid Connections

The general configuration suggested for the traction power system (TPS) is shown in Figure 5.3. A high voltage 'private wire' is connected at each end to the National Grid transmission network and is installed along the side of the motorway. Step-down Traction Power System (TPS) transformer/rectifiers supply power to the overhead line equipment (OLE) at regular intervals along the road.

This configuration is proposed because, as is explained in Chapters 6 and 7, the capacity to deliver power along the ERS routes will need to be expandable. In the early years, relatively few vehicles will use the network and power requirements will be low. As discussed in Chapter 2, it will take about 15 years for ERS-BEV penetration to reach 100% of the heavy vehicle parc so it would not be economic to build-out a full-power system right from the start. The private wire would enable the TPS units to be upgraded at a later date, or additional TPS units added, without any need for increasing the grid connections to the basic infrastructure.

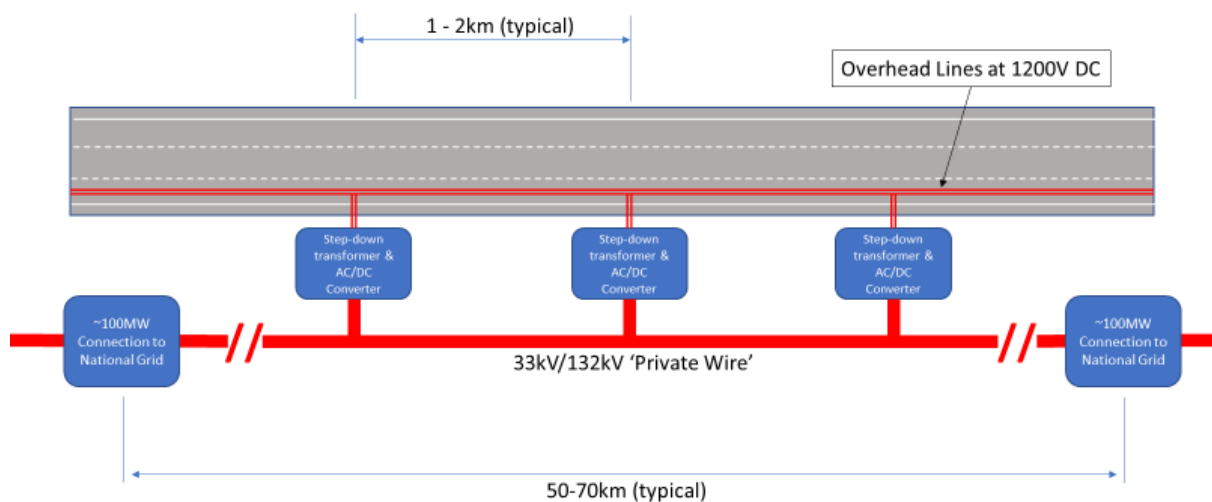


Figure 5.3: General configuration of the ERS traction power system.

5.1.3 Crash Protection

The masts used to support the overhead line equipment (OLE) are vulnerable to impact by passing traffic. Some form of crash protection needs to be provided and a solution would be to install a continuous steel or concrete barrier at the roadside. This approach was adopted in some of the ERS trials in Germany and a continuous concrete barrier can be seen in Figure 5.4 below. Continuous barriers are expensive and take time to install. Given the extreme length of the roadside which needs protecting (around 5,500 STK's for the system selected in Chapter 6) it would be worth exploring the development of less expensive solutions (see item 4) in Section 10.2.2).



Figure 5.4: Photograph showing the concrete road-side crash barrier installed for the German ERS demonstration project.

5.1.4 Junctions

A typical junction layout is illustrated in Figure 5.5. The length of motorway affected by the junction extends to the order of a kilometre with embankments, run-offs/run-ins, and bridges occurring within this length.

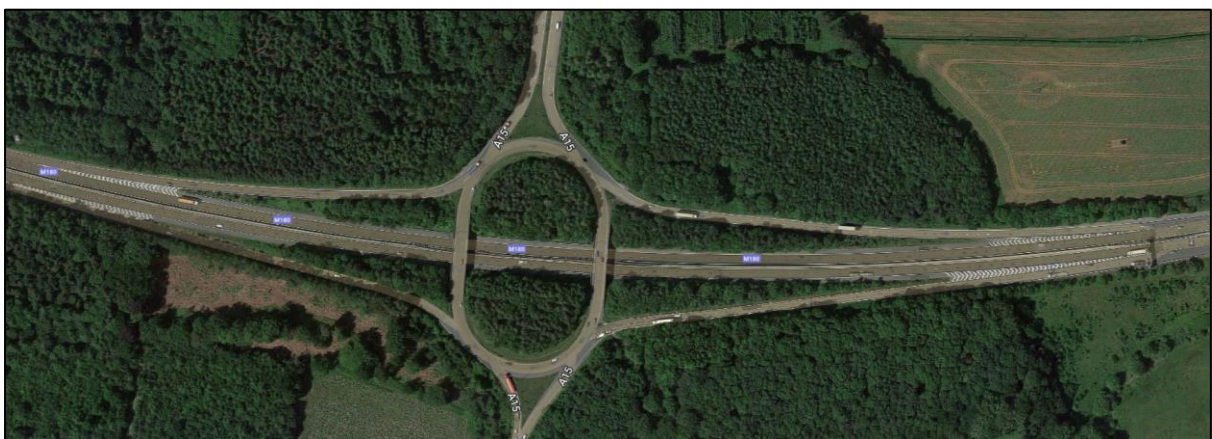


Figure 5.5: Satellite image of the topology of a typical UK motorway junction.

The simplest general solution to this class of obstacle would be to terminate the wires before the junction and resume them after the junction. Taking account of the need to retract the pantograph before the junction and raise it again after the junction means that anything up to 2 km of electrified wires could be lost at each major junction. This is not necessarily a major

problem in each individual case, but there are some areas on the motorways where many junctions occur within a short distance (e.g. the M1 in the vicinity of Sheffield where 9 junctions occur in the space of 27 km). In these areas, much greater lengths of electrification could be lost. Each such example will need bespoke consideration.

5.1.5 Low Bridges and Gantries

Low bridges and gantries require special consideration. In general, the OLE will be designed to pass underneath bridges and gantries without interruption, but there is a limit to the minimum clearance which can currently be dealt with in this way. This limit is set by the gap between the top of the tallest trailers which pass under the bridge (double-deck trailers can be up to 4.95 m) and height of the bridge soffit. For bridges/gantries with a soffit height of less than 5.2 m, there is not a sufficient gap between the soffit and the top of a double-deck trailer to run the wires under the bridge using conventional wire-support solutions. For bridges in this category, using currently available solutions, the wires will need to be terminated before the bridge and resumed after the bridge.

For infrequent occurrences of low obstacles, terminating and resuming the wires in this way is an acceptable solution. Unfortunately, this is a problem that is likely to be encountered quite frequently as is shown by Fig 5.6. There are over 200 low obstacles on the strategic road network.

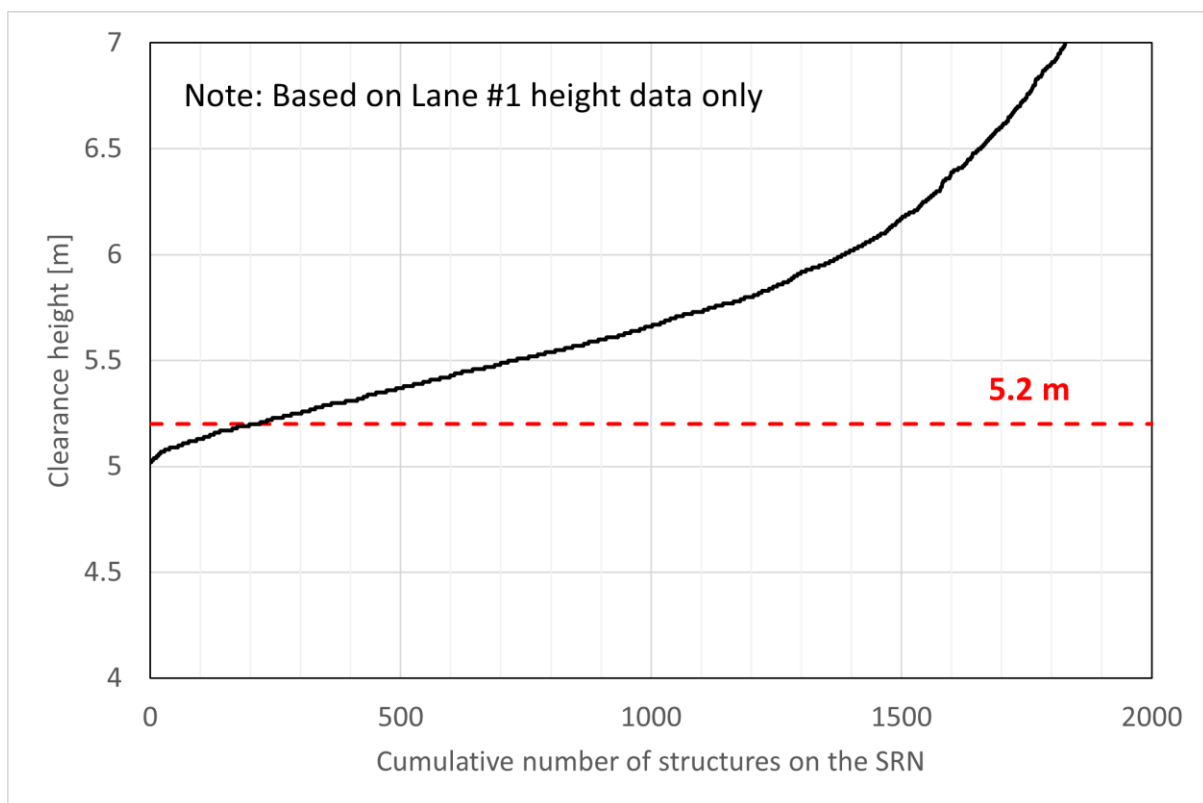


Figure 5.6: Distribution of structure clearance heights on the strategic road network.

On some parts of the proposed ERS network, many low bridges occur in close proximity to each other over relatively long stretches of motorway. This has the potential to disrupt power supplies over quite long distances (sometimes 20 km – 30 km). Figure 5.7 illustrates such a case where bridges with less than 5.2m clearance are plotted on a stretch of the M1. Given

the extent of this potential problem, it would be worth spending some considerable effort to produce a solution which enables the wires to pass under as many of these bridges as possible. A fuller discussion of the occurrence of low bridges may be found in Appendix E.

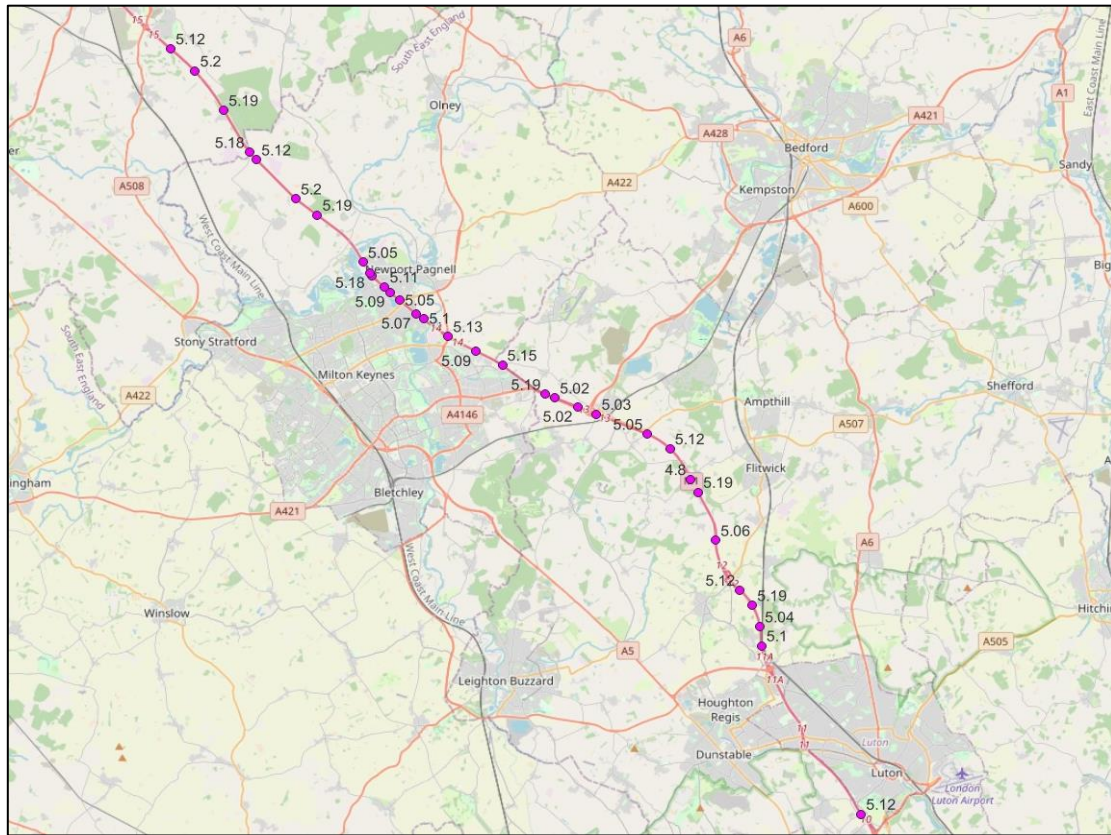


Figure 5.6: The occurrence of low bridges on the M1 between Luton and Northampton.

5.1.6 Smart Motorways

Smart motorways introduce two special considerations. First is the frequent occurrence of gantries for signs and signals. Provided the clearance height below these obstacles is more than 5.2 m (which is mostly the case), they pose no special problems other than the fact that the road-side space available to place the OLE masts might be quite congested and there might be obstructions to the line of sight with regard to the signs and signals. Both should be resolvable during the process of detailed design.

The second potential problem is the fact that HGV's commonly run in different lanes at different times of day depending on whether or not the hard shoulder is being used as a running lane. This means that vehicles with pantographs will need to be restricted to using a single electrified lane, or power will need to be provided over at least two parallel lanes. The latter approach will require larger masts with longer cantilevers from which to hang the wires. This is not a technology risk, but it will increase the cost of the OLE.

5.1.7 Metering and Billing

Once the ERS system has been commissioned, there will be many different vehicles using the wires as their source of electricity throughout the day. Auditable invoices will need to be raised by the operator of the wires and this gives rise to a need for robust metering and billing systems. It is not difficult to imagine that each vehicle will be given its own unique i/d which will be used to make the connection between drawing the electricity and sending the invoice.

Ideally, from the viewpoint of the operator of the wires, authority to draw electricity should be granted on the 'wires-side' of the system. In practice, it is difficult to see how this might be implemented. Authority to draw electricity may therefore have to be governed by equipment mounted on the vehicle-side of the system. This would dictate the development of a 'Weights and Measures' approach to metering and verification. This issue is similar to electricity metering for the railways and some cues could be taken from the rail application. However, the road application is more complex and a number of technical challenges will need to be resolved before a national system can be successfully deployed.

5.1.8 Monitoring and Control

Some means of real-time monitoring of the ERS will be essential. This will probably involve CCTV in addition to the normal site-wide communications and data acquisition (SCADA) systems which are now commonplace in railway electrification programmes. The system will need to be monitored continuously from a control centre (or multiple centres) and will also need to be connected directly to third parties (e.g. National Grid, local District Network Operators, blue light services, etc). Provisions will need to be made to trigger power isolation in the event of an emergency – either directly or via protocols which are established with the public emergency services.

5.1.9 Cyber Security

The system will need to have suitable protections against hackers and any other intruders with destructive intent. The consequences of an attack in which the national system is disabled would have an immediate effect on the population at large (empty shelves in the supermarkets, etc) and an extended period of disablement would result in serious harm to society and the economy.

5.1.10 Safety, Standards, and Interoperability

There will need to be comprehensive developments in the following areas before a national system can be fully specified.

- Safety Cases (for system installation and use).
- Highway standards for the approvals of overhead power lines and roadside equipment.
- International Standards to ensure interoperability.

5.2 The Static Charger Network

The static charger network comprises sites where vehicles can connect to the grid to re-charge whilst stationary. These sites can be located on two different types of property:

- (i) **Captive Properties** – meaning those properties which form part of the logistics industry and on which charging facilities will be funded by that industry (e.g. warehouses, retail sites, overnight fleet depots, etc.). A typical warehouse property is shown in Figure 5.7 below.



Figure 5.7: Photograph of a typical 'captive property' site (warehouse).

- (ii) **Public Realm Properties** - meaning those properties that are available for use within the public realm and must be funded by parties external to the logistics industry (e.g. private enterprise or government). These properties are further sub-divided into 'Service Areas' which are designated for daytime charging operations (represented by short period, high-power charging profiles) and 'Truck Stops' which are designated for both daytime and overnight charging (where overnight charging is characterised by long-period, lower power charging profiles). Typical 'Service Area' and 'Truck-Stop' sites are shown in Figure 5.8 below.



Figure 5.8: Photographs of typical 'public realm' sites – 'service area' (left) and 'truck stop' (right).

Key requirements for the static charging network are summarised in Table 5.3.

Facility Type	Specification	Key Assumptions
<i>Captive Property Sites</i>		
Depot-Based Overnight Facilities	Multiple chargers for fleet size. Typically 50/100kW per charger for 100 vehicles = 4-6 MW grid connection	Assumes 10 hours overnight charging window and power balancing software in operation on the charger system. Typical fleet size of 100 vehicles with 300-500 kWh battery packs.
Warehouse/Retail Outlet Facilities	Multiple chargers for loading bays. Typically, 600 kW per charger x 25 bays = 10-15 MW connection to grid allowing for some diversity of load.	Assumes part-charge during 20-minute dwell time at warehouse sufficient for 100 km driving (approx. 200 kWh – but re-charging limited by battery ‘C’ rate).
<i>Public Realm Sites</i>		
Service Areas	Multiple charger’s dependent on site size and prominence. Typically, 10 – 12 x 600kW chargers per ‘large’ site = 6-8MW MW grid connection	Chargers sized for 80% re-charge of battery within 45-minute driver rest period (approx. 400 kWh for a battery capacity of 500 kWh – re-charging limited by battery ‘C’ rate).
Overnight Truck Stops	Multiple chargers dependent on site size and prominence. Typically, 10 – 12 x 600kW chargers = 6 – 8 MW grid connection. PLUS Provision for overnight chargers (see next column)	As above, plus lower powered overnight charging facilities for vehicles undertaking multi-day journeys. Overnight charging facilities typically 20 x 100 kW chargers for vehicles with 500 kWh batteries and 20 x 200 kW chargers for vehicles with 1,200 kWh batteries. Assume that overnight chargers (100/200 kW) can be switched-in at the expense of daytime chargers (600 kW) to avoid the need for additional site connection capacity.

Table 5.3: Key requirements for a national static charger network.

5.3 Striking a Balance Between ERS and the Static Charger Network

The number and size of static charging sites required is dictated by the need to support a wide range of different journey types (see Chapter 3). Many of these journey types include a significant fraction of off-ERS movement and it is therefore essential to provide a network of static charging facilities across large areas of the country where electric HGV's might be operating far from the ERS.

Vehicle fleet operators will not be able to assume the presence of suitable chargers at all the destinations which they need to visit during a particular working day. Whilst 'Captive Property' installations *might* be made by individual organisations on a case-by-case basis, these will be based on their own operational efficiency considerations and will have no regard for national requirements. They cannot, therefore, be relied upon to provide a comprehensive network of static charging facilities which are accessible to all operators.

A national static charging infrastructure will therefore need to be installed regardless of any facilities which might be provided at Captive Sites. For some vehicle fleet operators, there will be many journeys which need to rely on public realm charging sites for 100% of their off-ERS charging requirements. This scenario defines the minimum acceptable pattern of coverage for the static charger network.

There are many possible configurations for the static charging infrastructure. Selection of the preferred configuration must take account of cost and other practical constraints. A specific build-out scenario is proposed in Chapter 6.

5.4 Strategies for Managing the Transition

The construction and commissioning of a national ERS system will take many years. This issue is discussed in more depth in Chapter 6 where it is suggested that the earliest date of commissioning even a preliminary system might be 2032 or later. With heavy electric vehicles beginning to appear in the second half of the 2020's, it is evident that there must be plans to address that period when vehicles are available but the ERS system is unavailable or incomplete.

There are two possible approaches to this problem. The first is to build-out a network of static charging sites which would enable vehicles with small/medium sized batteries to work some parts of the duty cycle spectrum across some parts of the country. The second is to accept the need for an interim period in which hybrid (range-extended) vehicles are used, thus allowing all duty cycles to continue to be operated across all of the country albeit with some reduction in emissions savings during the transitional period.

It is difficult to predict a precise transitional pathway. However, it is clear that pragmatic solutions are available. In practice, some combination of approaches is likely to be used.

6. The National Network – Delivery Strategy

In this chapter the practicalities of cost and programme are considered and this information is then used to inform the definition of a 'Preferred System'. The latter part of the chapter considers the practicalities of a national construction programme and suggests a timetable for national roll-out. This timetable is based on:

- A need to complete a reasonable length of ERS as soon as possible (on the basis that no ERS-enabled vehicles will be able to operate until a basic system is in place)
- The earliest feasible start date for construction work on site (taken here to be 2028).

6.1 Infrastructure Cost Base

6.1.1 The ERS Network

An illustrative 30 km stretch of electrified road has been adopted as the baseline for assessing costs. This baseline has been chosen because it is considered that the national roll-out programme could be most quickly delivered through a co-ordinated programme of 30 km section builds (see Section 6.3). Based on the detailed work carried out within WP5 (which has been costed at 2022 prices), the cost of building a 30 km single lane section of electrified road starting in 2028 is summarised in Table 6.1 below. All costs in the table refer to the electrification of a single lane (i.e. a one-way system).

The following important points should be noted:

- 2028 is identified as the 'start of build' This is considered to be the earliest feasible start date for work on site, driven by the need to complete a significant length of ERS before the first ERS-enabled BEV's can be deployed.
- 2028 costs are estimated to be lower than 2022 costs because of the learning and process/technology improvements which can be anticipated over the intervening period. These are itemised in the 'Assumptions' column.. A constant value of money has been assumed.

Category	Item	Cost (0.5 MW/STK)	Assumptions
Design	Civils Design Power Supply (Included in 'Direct Works' Packages below) OLE (Included in 'Direct Works' Packages below)	£3Mn (£100k/STK)	Assumes significant design efficiencies will be achieved by 2028 as a result of increasing automation.
On-Site Preliminaries	Site Office Complex Construction Management Temporary Works Traffic Management	£21Mn (£700k/STK)	Assumes significant process & organisational improvements will be achieved with DfT committing to a long-term 'Programme Approach' to procurement. Assumes a construction approach can be developed to enable a 'no contraflow' working arrangement during build-out.
Direct Works: Civils	Permanent Crash Protection Plinths for Sub-Stations Bridge Modifications Drainage, Earthworks and Landscaping Electrical, Communication, Lighting, & Signage Miscellaneous	£19Mn (£633k/STK)	Assumes normal rates of continuous improvement.
	Grid Connections	£3Mn (£100k/STK)	Assumes major improvements in grid connection costs as a result of a long-term plan, greater transparency, and possible change in policy.
Direct Works: Traction Power Systems and Overhead Line Equipment	Traction Power Systems (inc. Sub-Stations)	£8Mn (£270k/STK)	Assumes major improvements in TPS unit costs due to long-term purchasing commitments and the economies of volume manufacturing.
	Masts and Catenary Systems	£18Mn (£600k/STK)	Assumes normal rates of continuous improvement.
Other Costs	Land Costs, Statutory Undertakers NR VAT Lead Contractor Fee	£15Mn (£500k/STK)	Assumes significant improvements as a result of adopting a long-term programme approach.
TOTAL (£M)		£87Mn	
COST/STK		£2.9Mn/STK	

Table 6.1: Estimated ERS Construction Costs at 2028 (constant 2022 value of money).

The conclusion of this analysis is that build costs at 2028 would lie in the region of £2.9Mn/STK for a system which meets the 'lightly trafficked' specification outlined in Table 5.2. This figure will be used in Section 6.2 below to calculate the cost of delivering the 'Preferred System'.

6.1.2 The Static Charger Network

The spatial distribution of the large and small static charger sites must ensure that every vehicle operating off-ERS will always be within a short distance of several different charging sites. Based on this consideration, it is estimated that the Public Realm charging infrastructure will ultimately need to comprise around 2,100 sites nationwide. This might be made-up of some 1,600 large sites (typically equipped with 10-12 x 600 kW chargers) and 500 small sites (typically equipped with 2-3 x 600 kW chargers). This number of sites corresponds to an average density of around 1 site every 100 sq. km (equivalent to a 10 km x 10 km grid). Busy areas of the country would have a preponderance of large sites; less busy areas would have a preponderance of small sites.

In defining this site density, it has been assumed that operators will have access to real-time information systems which can plan daily itineraries and select/reserve charging sessions in advance. It is reasonable to assume that, by the early 30's, such systems will be capable of ensuring that no vehicle will arrive at a static charging site to find a queue, a lack of connections, or a shortfall in charging capacity.

An important segment of the logistics industry is engaged in 'tramping' operations. These journeys frequently involve multi-day duty-cycles and provision for overnight stops/re-charges therefore needs to be included in the design of a national system. Accordingly, 10% of the large sites have been designated as overnight 'Truck Stops' with suitable additional overnight charging facilities (20 ERS-BEV vehicles at 100kW per connection). In the case of the 'Big Battery' scenario (BB-EV's), this overnight capacity would need to be raised to 20 x 200kW connections.

The number of chargers available nationwide will need to be commissioned progressively as the fleet of ERS-BEV vehicles increases with time. (This is in line with the Transition Strategy discussed in Section 5.4). Once the initial sites have been commissioned, the subsequent capacity upgrade could be achieved by increasing the number of chargers installed at each site, or by building new sites with more chargers in different locations.

A representative programme of static charger build-out is shown in Table 6.2. It suggests a certain rate and style of growth but, in reality, the detail of build-out will need to reflect the actual levels of demand.

By 2040, it is anticipated that some 1,600 large sites and 500 small sites will need to be operational. The cost of installing and connecting a low powered site (typically 3 x 600 kW chargers with a site connection rated at ~2 MW) would be in the order of £1M including grid connection costs but excluding land purchase. The comparable cost for a large, high powered site (typically 8-12 x 600 kW chargers with a site connection rated at ~7 MW) would be in the order of £3.4M, again including grid connection but excluding land-purchase. The background to these figures is presented in Appendix F.

Year	2030	2035	2040	2045	2050
No of EVs on the Road	1,611	49,941	130,490	190,096	193,318
Large Sites	500	750	1,200	1,600	1,600
- No. Vehicles/Day	2	43	70	76	77
- No. Pumps	3	6	9	10	10
Small Sites	500	500	500	500	500
- No. Vehicles/Day	2	2	4	6	8
- No. Pumps	2	2	2	2	2
Overnight Sites	50	75	120	160	160
Nominal Charging Capacity (No. Lorries per day)	2,000	33,250	86,000	124,600	127,200
Peak Charging Capacity using all 'Reserve' Margins (No. Lorries per day)	5,093	40,354	111,374	158,077	162,655
Static Charger Network Cumulative Cost	£0.9 Bn	£2 Bn	£4.2 Bn	£6 Bn	£6 Bn

Table 6.2: Build-out programme for public domain static charger sites.

The considerations that define the number of sites and the number of chargers are:

- (i) The aggregated capacity of the Public Realm sites must be designed to exceed the maximum reasonable demand of the 'off-ERS' fleet on any day. This excess capacity must be provided to ensure that random spatial distributions of vehicles do not cause congestion problems at charger sites and lead to unacceptable journey delays.
- (ii) Chargers at all daytime Service Areas (both large and small sites) will be rated at a minimum of 600kW per connection, thus ensuring that a lorry with a 500 kWh battery can receive an 80% charge within a driver rest period of 45 minutes.
- (iii) A BB-EV vehicle (1,200 kWh) using 600kW chargers will be able to take ~400 kWh charge during a 45-minute break. This is sufficient for an onward journey of 200-250 km (depending on conditions) and is considered to be sufficient to ensure a return to home base or an overnight truck stop under all foreseeable conditions.
- (iv) The number of chargers at each individual site must be designed to serve peak (not average) demand. The design peak has been calculated by specifying that 70% of charging events each working day occur within a core period of 10 hours. On top of this, a 'surge factor' of x1.5 has been applied to account for increased vehicle activity during peak periods and, finally, a 20% increase in the overall charger numbers has been added to account for equipment failures and scheduled downtime.

6.2 Selecting the Preferred System

A suitable national system must enable the logistics industry to continue delivering current levels of customer service without forcing unnecessary changes of operational behaviour and without imposing undue additional costs. The preliminary studies carried out to date suggest that the best means of achieving these goals would be to develop a charging infrastructure which comprises:

- A 'Light' ERS Catenary System' (network length approx. 5,500 lane-km)
- 1,600 'large' public realm static charger sites, of which 160 have overnight 'lorry stop' facilities
- 500 'small' public realm static charger sites at infrequently used locations (no special overnight facilities)

This configuration has been arrived at by simulating numerous journey-types from the envelope of cases described in Chapter 3. From Table 3.2, the adoption of a system of this configuration would result in:

- 100% of all journeys being serviceable with a vehicle battery size of 500 kWh.
- The average increase in aggregated journey time across the entire fleet would be around 0.5% as a result of stopping for static charging
- The single worst case increase in journey time as a result of stopping for static charging would be around 15%

Vehicles with smaller batteries than 500 kWh could be adopted for many journey types as has been noted in Chapter 3.

In addition to the agent-based analyses described in Chapter 3, a sub-set of 'corner case' journeys was examined in which specific locations were identified for the wayside charging points. This was done using a detailed vehicle simulation model as described in Appendix G. The purpose of these simulations was to confirm that the charger location strategy which has been proposed provides a workable solution for 'real' journeys at the practical level.

An example of a complex multi-drop journey in the South of England which was examined in this way is shown in Figure 6.1. Different charging tactics were assessed in these analyses exploring, for example, the effects of changing the driver mandatory rest period from a single 45-minute break every 4.5 hours into two split break periods which sum to the same rest time. (This allows static charging to take place at different points along the route without introducing an overall time delay during the working day). The key results are tabulated in Table 6.3.

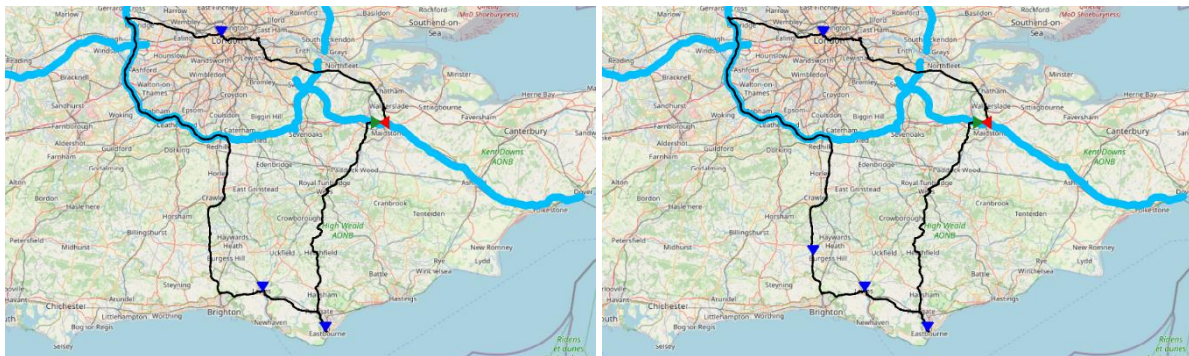


Figure 6.1: Multi-Drop 'Corner Case' studies (conventional rest stops left, BEV rest stops right).

Aylesford Eastbourne (retail)	Required battery capacity (kWh)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	818	588	366	342
Charge at drop-off sites (600 kW)	336	226	223	223
Charge at public rest stops (600 kW, 45m)	N/A	N/A	N/A	N/A
Charge at public rest stops (600 kW, 30+30m)	454	373	342	342

Table 6.3: Aylesford Eastbourne (retail) – summary of required battery capacity for an ERS-BEV.

The bottom row of Table 6.3 (in which charging takes place at public realm static charging sites, and mandatory driver rest periods are split to accommodate two brief charging sessions) confirms that the proposed number of static charger sites (1,000 initially, rising to 2,100), sited on A-roads and distributed across the country in a pattern which reflects the density of demand, would be sufficient to provide the necessary support to the electric vehicles servicing this route without any need to extend the working day.

6.3 The Deferred Build-Out Strategy (DBOS)

Table 5.2 sets down the proposed design parameters for a national ERS network. It refers to linear power demand levels which relate to lightly trafficked and heavily trafficked elements of the network. At this stage, it is not clear how much of the final network will need to be serviced with the higher level of power delivery so it would make sense to build-out the entire network at the lower power level to start with and then progressively upgrade those sections which are seen to be necessary in the light of operational experience. This is an appropriate approach because it will take time for the numbers of electric lorries on the road to build up to a significant proportion of the heavy lorry parc and, during this initial period, electric heavy lorries will represent only 'lightly trafficked' numbers for the power delivery system. (It is estimated in Chapter 2 that the proportion of electric vehicles in the heavy lorry parc is only expected to reach 25% penetration by around 2035).

Deferring the full cost of build-out in this way helps to improve the overall financial equation for two reasons:

- Only those sections which are seen to be necessary will be upgraded to the higher power level during the later phase of build-out, thus avoiding unnecessary expenditures.
- A significant portion of the total expenditure will be delayed, thus making the expenditure profile come into much better alignment with the revenue generation profile.

For ease of reference hereafter, this will be referred to as the 'Deferred Build-Out Strategy' (DBOS).

6.4 The Construction Strategy

A natural drawback with the ERS concept is that a significant fraction of the total system needs to be commissioned and working before the intended vehicles can make use of it. Achieving the target of net zero emissions by 2050 therefore puts pressure on deploying the charging infrastructure as soon as possible so that the initial take-up of ERS-enabled vehicles is not unnecessarily delayed.

As mentioned in Section 6.2, it will take around 15 years between the first ERS-enabled lorries appearing on the road and the heavy vehicle parc becoming 100% electric. Working

backwards from the aim of achieving 100% electric vehicles a few years in advance of 2050 suggests that the initial phases of the ERS system will need to be functional no later than the early 2030's. This, in turn, implies a start of construction sometime before 2030. This early start date and compressed delivery timetable sets a very difficult challenge from a construction point of view.

It is generally accepted in professional circles that building roads, railways and other major items of infrastructure in the UK costs significantly more and takes significantly longer than it does in many other parts of the world. This disparity is particularly marked in the comparison with Asia-Pacific countries. There needs to be some effort to close these gaps if the delivery targets suggested here for the ERS programme are to be met.

To put this challenge in context, however, it is worth noting that a major effort is needed to shorten UK construction programmes in any case. This need is driven by the UK commitment to meet its 2050 Net Zero targets and applies primarily to the need to build power generation and transmission/distribution capacity. In national terms, this is a much more significant issue than heavy road freight. (In passing, it is also worth noting that a hydrogen strategy would accentuate the national power generation problems even more because of the need to power the electrolysis process and the inherent inefficiency of the hydrogen approach).

6.4.1 DBOS Stage 1 – The Low-Power Phase

Focusing on the need for speed, the national roll-out of the initial phase of the ERS system could be delivered most rapidly through a series of Framework Agreements which are openly tendered and placed with suitably qualified and experienced contractors. These contracts would provide long-term commitments to the contractors and enable them to take a 'Programme Approach' to delivery as suggested in Table 6.1.

Within each Framework, the work could be executed in a series of 30-km Section lengths, delivered in a sequence designed to minimise time to completion whilst limiting inconvenience to normal road users. The details of the sequencing would need to be defined in discussion with National Highways.

An outline programme for the construction of a 30 km section of ERS is shown in Figure 6.2 below. This programme relates specifically to time on-site. It does not include:

- The time required in advance of start-up for planning and permitting,
- The lead time required to 'book' the electricity supply connections with National Grid.
- The design and manufacturing lead-time for the TPS and OLE

It is assumed that these long-lead items can be dealt with during the period 2025 – 2028 and, as a result, the detailed design and the supply-chain gear-up for each 30-km section will be complete before any work starts on site.

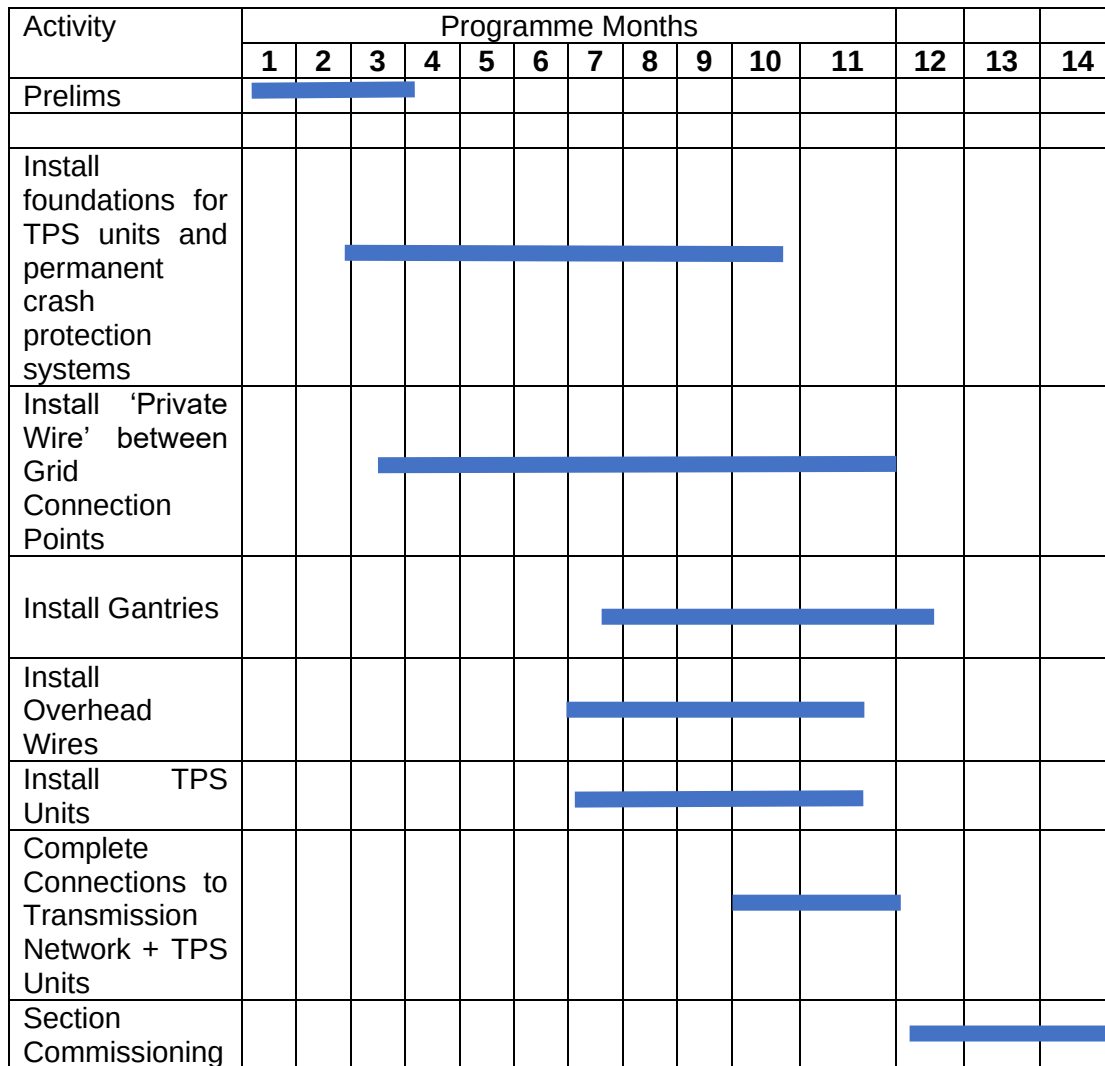


Figure 6.2: Illustrative construction programme for 30 km stretch of single-lane ERS.

The construction programme illustrated above would require about 100-150 site workers. This averages out to around 5-6 worker-years per STK. Some additional resourcing would also be required for site-office based positions (e.g. construction management and supervisory staff) and manufacturing jobs (e.g. TPS and OLE equipment supply).

Based on the programme and manpower estimates for an independent 30 km section of single lane electrification, an estimate has been made for the time and resources which might be required to construct and commission the first phase of the national network (5,500 STK). This estimate has been based on the following assumptions:

- It is accepted that the construction of the ERS system is a national priority which requires extraordinary measures if it is to be completed on time.
- The initial phase of the ERS Network comprises around 5,500STK with an average power rating of 0.5MW/STK throughout the system.
- The entire construction programme is let via tender under 9 parallel, long-term, independent Framework Agreements for design, construct, maintain, and operate.
- The 9 Frameworks are defined geographically as shown in Figure 6.3.

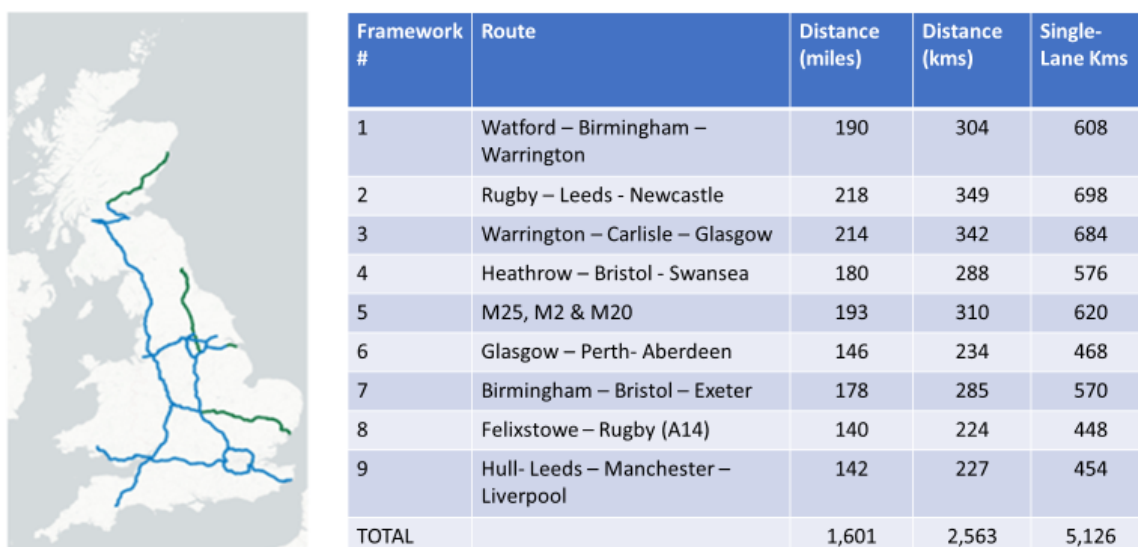


Figure 6.3: The proposed nine framework contracts to construct 5,500 STKs of ERS.

The time required to deliver each Framework Route will depend on the construction sequencing of the 30 km Sections contained within the route. The details must be determined in discussion with National Highways based, principally, on the need for rapid and safe delivery, and public toleration for traffic disturbances.

The fastest route to delivery, in theory, would be to electrify both sides of the carriageway in 30 km sections simultaneously along the entire Framework route length. This approach, however, would be unacceptable from a traffic disturbance point-of-view. The next fastest alternative would be to stagger the delivery of the 30 km construction sections so that on either carriageway there are acceptable gaps between sections of road-works. This principle is illustrated in Figure 6.4.

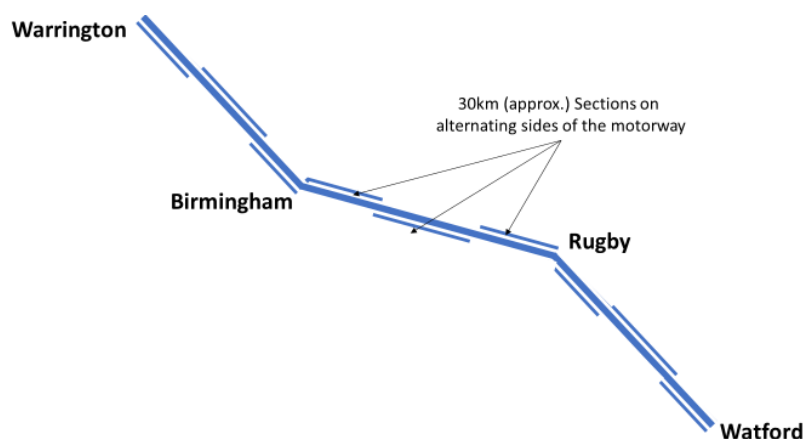


Figure 6.4: Proposed staggered build sequence designed to minimise construction time and reduce traffic disruption to acceptable levels.

Staggering the construction on either side of the carriageway, and building the staggered sections in parallel, would lead to a minimum credible construction period for Framework 1 of approximately 30 months (with similar durations for the other frameworks). The programme would create around 1,500 site-based jobs on Framework 1 for the duration of the construction period. Scaling these jobs to include all 9 Frameworks according to the length of each route (see Figure 6.3) leads to a national total of approximately 10,250 site-based jobs over a period of 3 years (which allows some float in the minimum timetable to allow for practicalities). This

represents the minimum credible construction period which might be achieved under extreme circumstances. A more realistic estimate might be 4 years which would result in the creation of around 7,700 site-based jobs for the duration of the work.

In addition to the site-based jobs, there would also be a considerable number of factory-based jobs associated with the design, manufacture, and supply of TPS and OLE equipment. This is likely to add another 500 – 1,000 jobs in service of the construction programme depending on the details of the procurement and build-out strategy.

Delivering a total of 5,500 STK's over 4 years is well beyond anything that has been achieved in the UK on rail electrification programmes in the post-war era. The best build-rates achieved in the UK rail industry over the past 70 years have been around 500 STK per year. A target of around 1,400 STK's per year would therefore be seen as a National Challenge. This target is clearly well beyond historic performance statistics but this factor, in itself, does not mean the target cannot be met. The target rates of build-out have been frequently achieved in the Asia-Pacific region and the feasibility of doing the same in this country needs to be assessed.

There are several bounding constraints on how fast the DBOS strategy could be delivered. These are:

- (i) The time it takes to build a typical section. In this case, the typical section is 30 STK's. It is considered that this can be delivered using today's best practice in a period of 12-14 months with a site staff complement of between 100-150 workers.
- (ii) The number of sections that can be built in parallel. This depends on National Highways, who will not accept continuous roadworks over long stretches. The general rule is that there should be at least 10 km of free running on any carriageway between stretches of roadworks. Using this guidance, it makes a big difference if the traffic management strategy can avoid using contraflow arrangements. This is an important subject for further investigation but, assuming such an approach can be developed, the build-out programme could be staggered along a Framework Corridor as suggested in Figure 6.4, leading to the completion of a Framework Corridor in approximately 3-4 years. Since the Framework Corridors are largely independent, all the corridors could be constructed in parallel if the need is deemed to be great enough.
- (iii) The numbers of Site-Based Workers Required. There must be an upper limit to the number of sections that can be built in parallel because, at some stage, there will be a constraint on the number of workers and equipment/plant which are available in the country. If it takes 3-4 years to build out the national system, it would require a site labour force over that period of approximately 8,000 – 10,000 workers. These are large numbers, but not large enough to stall the whole of the UK Construction industry (total workforce = 1.4M). By comparison, there will be around 6,600 workers on-site continuously at Hinckley C Power Station during 2022.
- (iv) The Amount of Plant Required. In addition to staffing limits there are material and equipment limits. There will be an abnormal demand for specialist equipment during the construction period (e.g. piling machines, OLE-stringing equipment), but the numbers involved do not suggest that this need cannot be met by ordering more machines or more material *provided the commitment to build is declared at a sufficiently early stage.*
- (v) The rate of supply of factory-built components. The TPS and OLE equipment will be supplied by manufacturers who will build the equipment in factories prior to delivery to site. These manufacturers and their supply chains will need to gear-up to provide the numbers of units required (some 2,000 TPS units plus 5,500 STK's of OLE equipment) and this might exceed the current capacity which is available within the UK. TPS units and OLE units, however, can be purchased from a variety of manufacturers across the world and it is considered very unlikely that the numbers

required here would exceed the capacity of the global supply chain, *provided the commitment to purchase is declared at a sufficiently early stage.*

- (vi) The number of Professional Designers and Skilled Trades Required. This is probably the most problematic area, because there is currently a limited number of such specialists in the UK and Europe. There are also competing demands from the rail electrification programmes (although these might, equally, pave the way for a ramp-up in national capability). It is assumed that all the design work will be completed over several years before construction begins, so this element is excluded from the 3-4year construction time estimate. Also, it is assumed that the design work will be shared out between specialist providers and multiple international consultants who, between them, can draw on resources based overseas in addition to home-based resources. In the meantime, detailed design will become less labour intensive because of the increasing use of automated systems. In combination, it is considered that these factors should enable the design challenge to be met *provided the commitment to build is declared at a sufficiently early stage.*

It is unlikely that the UK will be the only country building out an ERS system over this period and there might be competition between infrastructure projects across Europe. There are two good ways to mitigate this problem. First, start as early as possible and 'beat the rush', thereby scaling-up the UK industry before other European countries. If managed correctly this would provide a huge opportunity for exporting UK engineering, manufacturing, and construction capabilities to Europe. Second, it would be sensible to coordinate engineering and construction resources with other European countries so that all projects can benefit from the large scale of the operations.

In summary, it is recognised that to build 5,500 STK's in 3-4 years represents a national challenge. It would require a combination of world-class project organisation and single-minded determination to meet the proposed 2032 completion target for Phase 1. But, if the need is seen to be a national priority, there appears to be no fundamental reason why it could not be done. Grand challenge projects from the past, exemplified by the London Olympics and HS1, speak to the ability of UK industry to rise to the challenge given the right leadership and support by government.

6.4.2 DBOS Stage 2 – High Power Upgrade

It is assumed that the low-power phase will be ready for service starting around 2032 and will have been built-out at an average cost of £2.9Mn/STK (see Table 6.1). By 2035, if all goes well, electric vehicles will account for around 25% of all heavy lorries on the roads and the system will be nearing its limits of power on the most heavily trafficked parts of the network. A similar situation will also be reached with the static charger network. At this time, both parts of the system will need to be progressively upgraded so that higher levels of power can be delivered on those sections of the network which are seen to require it (up to a likely maximum of 2 MW/STK on the ERS wires, and up to a maximum of 2,100 sites for the static chargers).

Taking advantage of the expandable characteristics of the Traction Power System described in Section 5.1.2, it is suggested that the low-power TPS units delivered in Phase 1 can either be expanded in a modular fashion, swapped-out and replaced with new, more powerful units, or supplemented with additional units at intermediate locations. Provided the connections to the grid (the 'Private Wire') and the TPS plinths have been sized and located correctly during Phase 1, the upgrade operation can be carried out with minimal disruption when it becomes necessary with new units being craned into place and connected overnight on a location-by-location basis following the precedent set by the railways.

For the purposes of developing the financial aspects of the business case (see Chapter 7), a worst case has been assumed. It is postulated that the entire network is built-out to a power density of 2MW/STK and that the upgrade phase of construction progresses at an even rate of expenditure (£550Mn per annum) during the period 2035 -2045 inclusive. Under this scenario, the total cost of construction will have risen by the end of the upgrade period from £2.9Mn/STK to £4Mn/STK (per the costs for 0.5 MW/STK and 2 MW/STK shown in Table C.6 (Appendix C)).

6.3.3 Construction of Public Realm and Captive Property Static Charger Sites

Construction of the public realm (wayside) static charger sites has not been included in the above discussion because these sites can be delivered independently of the ERS network. The development of sites with multiple chargers suitable for electric cars is already common practice. It is likely, therefore, that each HGV site would be built out by a private charge point operator (CPO) working through local contractors. The same argument applies to that sub-set of these facilities which are designated as overnight stops (lorry stops). To build some 2,100 static charger sites over four years is considered to be well within the capacity of the UK industry noting, however, that the order lead-times for charging equipment and grid connections will be critical path items and must be dealt with in good time.

Installation of static charging infrastructure at destination sites (warehouses, retail outlets, etc) is considered to be a matter for the attention of the logistics operators. Such installations will need to be dealt with on a case-by-case basis, based on an appreciation of the business benefits which could be delivered in each particular case. As discussed in Chapter 3, destination chargers directly benefit the owners of the destination sites. Their presence, or absence, cannot be relied upon to help the public realm charging infrastructure to serve its purpose. For this reason, the provision of destination charging facilities is not included in this analysis.

Finally, in like manner, the installation of overnight charging facilities at fleet depots is also considered to be a business decision to be taken by the VFO's. The cost of these installations is attributed directly to the vehicle TCO's as presented in Chapter 4. No part of this cost has been included in the national infrastructure programme.

7. Business Case

This chapter introduces the business case. It is presented in three parts - the Financial Case, the Environmental Case, and the Social Case. The detailed analyses which provide the justification for the arguments presented here may be found in Appendices A & C. Throughout this Chapter, unless otherwise stated, several important factors remain unchanged:

- All arguments relate to the 'Preferred System' which was defined in Chapter 6 (i.e. the ERS 'Light' network supplemented by a public network of some 2,100 static charger sites).
- The price of electricity remains constant over time at levels which were relatively stable before the energy crisis (namely 5 p/kWh wholesale generation price and 12 p/kWh bulk user retail price).
- For the investment assessment, Net Present Value calculations are adjusted to start at the date at which significant infrastructure expenditures are incurred (i.e. the proposed start of build-out in 2028).

7.1 Financial Metrics

The financial case is examined from two different perspectives.

- (i) *The 'Free Market' Scenario* – in which government mandates a change to zero emission vehicles and then steps back and allows the free market to develop an appropriate solution. Under these circumstances, every commercial participant seeks to maximise their own rewards.
- (ii) *The 'Government Intervention' Scenario* – in which government intervenes to ensure a desired outcome or to deliver a solution in the event of a market failure. Under these circumstances, there is a need to find a solution which delivers the greatest value for money to the Public Purse.

7.1.1 The Free Market Scenario

A free market will naturally create a balance between the needs of the users (the vehicle fleet operators, or VFO's) and the needs of the providers (the infrastructure owner/operator).

Assuming the flexibility and reliability of BB-EV's, ERS-BEV's and HFC-BEV's will ultimately match that of diesel vehicles, the critical element in the VFO's choice of technology will be TCO. The principal needs of the VFO's have already been discussed in Chapter 4 and some of the key points raised there are further developed in this section.

In the case of ERS versus hydrogen technologies, Figure 7.1 shows how the TCO at 2035 varies according to the price of electricity 'at the wires' in the ERS solution, and the price of hydrogen as delivered to the VFO depot. 2035 has been selected because it represents the point where the Phase 1 ERS system has been completed and ERS-BEV sales might be expected to rise sharply.

Figure 7.1 shows what prices can be tolerated at the wires before the cost of operating ERS-BEV's rises to match that of HFC-BEV's. In this case, for simplicity, it has been assumed that the VFO purchases 50% of the electricity at the overnight depot and 50% from the wires during the working day for all sizes of vehicle battery. (Note: This is a slightly different set of base assumptions from those presented in Chapter 4 where a similar analysis is described). The price of hydrogen has been varied between £3/kg and £7/kg. For reference, the price of *green*

hydrogen delivered to the VFO's at 2035 has been calculated to lie between £3.80/kg and £6.90/kg, corresponding to the source prices of electricity varying between 5 p/kWh (captive generating plant) and 12 p/kWh (grid-supplied electricity). The results show that the price of electricity at the wires can vary within the range 20 p/kWh – 80 p/kWh depending on the price of hydrogen which needs to be matched.

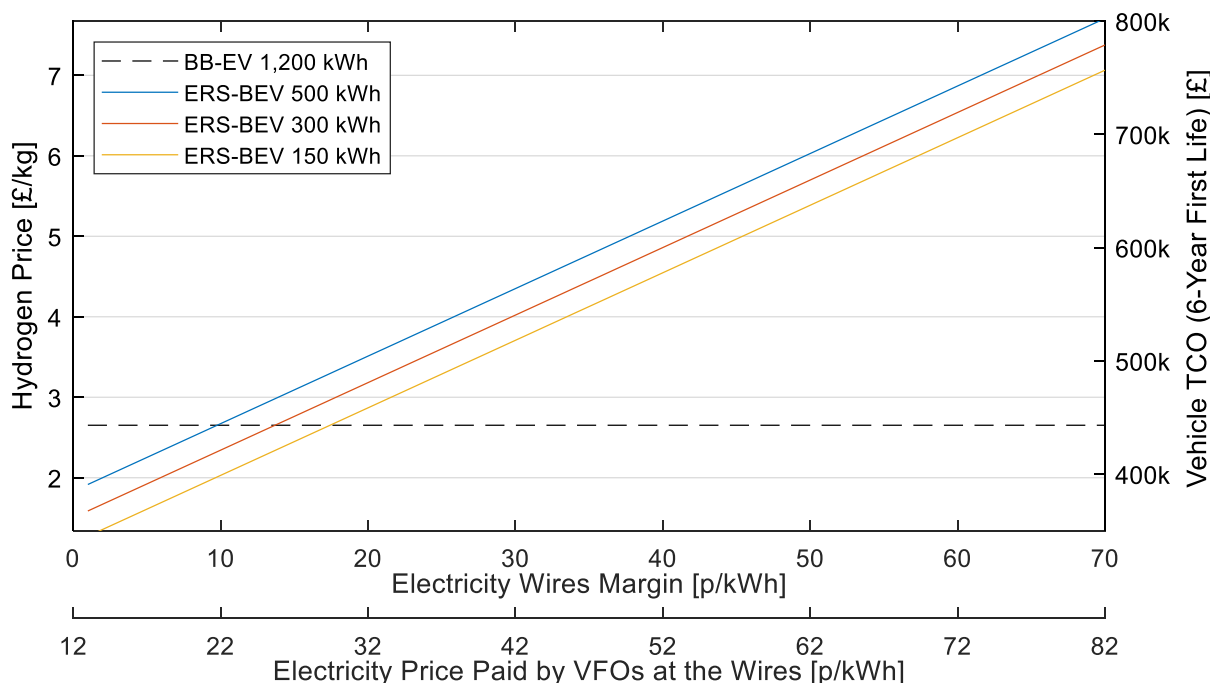


Figure 7.1: Price of Hydrogen (£/kg) versus electricity price/margin chargeable at the wires for ERS-BEV's with different battery sizes (2035).

The BB-EV case is also shown on Figure 7.1. In this case, the TCO for running a fleet of vehicles is not dependent on buying any electricity at the wires. Rather, it is fixed by the cost of installing a larger charger facility at the overnight depot and the price of purchasing electricity 'at the socket' (12 p/kWh). The BB-EV TCO at 2035 is projected to lie at around £430,000 and the matching price of electricity from the wires lies in the range 15 p/kWh – 30 p/kWh. This suggests that, from a purely financial perspective, the BB-EV solution could be more attractive to the VFO than either the hydrogen solution or the ERS solution if the price of electricity at the wires sits above this price band. This puts a severe constraint on the business case for building the ERS.

There are, however, some important drawbacks with BB-EV's which could affect this conclusion. First, batteries are the 'Achille's Heel' of electric vehicles. They require a lot of energy to produce and the embodied CO₂e is high (typically 100 kg/kWh, or even more, at the time of writing). This suggests that for a battery sized at 1,200 kWh, each vehicle would be responsible for more than 100 t of embodied CO₂e at the point of manufacture and twice this figure over a working life of 12-15 years because of the probable need for battery replacement at around 6-8 years.

Batteries also embody materials which are either unpleasant, difficult to obtain, or are extracted under socially unacceptable conditions (e.g. lithium, cobalt). This raises ethical and environmental questions in addition to the disposal question. Recycling technologies are in their infancy and the real scale of the disposal issue is not clear.

In combination, these considerations suggest that battery sizes should be minimised wherever possible. The 'Big Battery' approach, therefore, runs counter to the requirement to minimise environmental impact and should only be considered with caution.

Separate from the environmental impact considerations, there are also some negative practical/operational considerations associated with Big Battery vehicles. The need to charge very large batteries at their home depots will place heavy loads on the electricity distribution networks local to each depot. Demands could lie in the range 10 – 15 MW for a depot with 100 vehicles. For such depots, the necessary grid connection could exceed the capacity of the local district network, leading to a need for extensive and costly network upgrades in that locality. In addition, the weight of the battery (around 8 t – 9 t for a 1,200 kWh vehicle) will put limits on the maximum revenue-earning payload of the vehicle. Around 40% of all journeys are weight-limited, so any reduction in load hauling capacity per vehicle would require additional vehicles to be operated. The effect of this increase in fleet size on the total cost of operations has not been investigated here but it is known that, for this reason, some fleet operators put a price on increased tractor weights when making their purchasing decisions. (In one case, it is known that a price of £40/kg has been used as the increase in first-life TCO which results from reduced payload capability. For a Big Battery vehicle, this could accrue to a first-life TCO disadvantage in excess of £200,000). Given the potential size of this cost disadvantage, the weight penalty factor requires more detailed study.

Figure 7.2 below shows the potential return on an investment to build the ERs system. The diagram is based on NPV calculations which assume the construction cost is funded by project finance at 6%p.a. and that the revenues are generated from sales of electricity at the wires. The quantities of electricity sold in each year reflect the transition curve from diesel to electric vehicles as presented in Chapter 2. The selling price of electricity at the wires is shown as a variable on the horizontal axis. The diagram shows a range of possible NPV/price relationships which correspond to different percentages of heavy lorry electricity that are purchased at the wires (30%, 50% and 70%). The balance of electricity consumed by the vehicles is assumed to be purchased by the VFO's at their overnight depots or at wayside static charging stations.

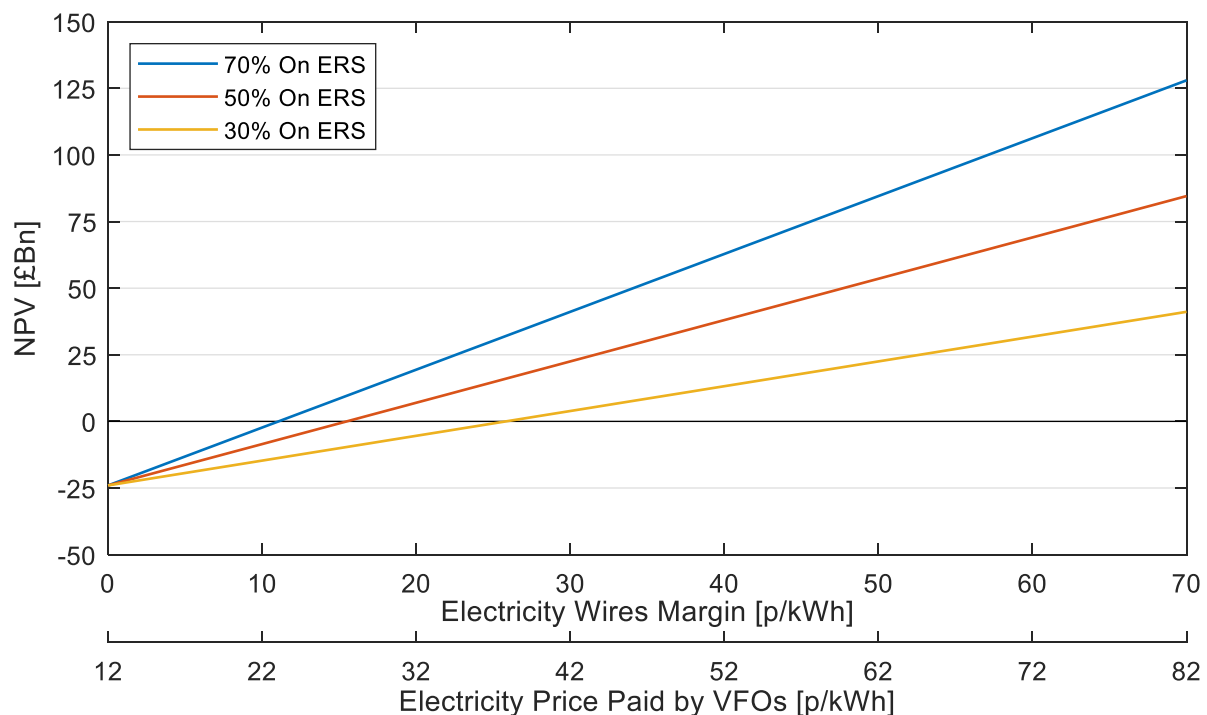


Figure 7.2: Free Market Scenario: Infrastructure NPV (2025-2050) versus selling price of electricity to VFO's at the wires for different levels of system utilisation.

If hydrogen sets the thresholds for the price of electricity at the wires (20 p/kWh – 80 p/kWh, from Figure 7.1), Figure 7.2 suggests that a private company willing to make an early investment in building-out the ERS could make a good return on the investment over a large part of the envelope of electricity prices (at the wires) and system utilisation rates. If, on the other hand, the electricity prices at the wire are set by BB-EV, the NPV of the system makes an unattractive return for any developer/operator of the ERS system.

The uncertainty about the presence, or absence, of BB-EV's, plus some other unquantifiable uncertainties about future transport technologies, economic circumstances, and societal attitudes, represent big risks for a private developer/operator. Given the multi-billion pound investment required during the build-out period (around £16Bn for the initial low-power network, followed by another £6Bn for the subsequent high-power upgrade) it is very unlikely that a private company would accept these risks. Even if one did, based on the likely price of electricity at the wires the 6-year TCO for a vehicle at 2035 based on a constant value of money would rise from around £400,000 today to more than £700,000. This might be considered to be unacceptable from a social/political perspective, given its likely effect on the prices of goods in the shops. The implications of this are discussed in the next section.

7.1.2 The Government Intervention Scenario

If no private enterprise would be willing to make the necessary investment, or if the increase in transport costs associated with a free-enterprise environment is considered to be unacceptable, the alternative would be for the government to fund the build-out of the ERS network and its associated static charging sites. This decision would be based on the ability of the ERS solution to produce a zero-carbon outcome and its resulting value as a social good. Under these circumstances, selecting ERS as the favoured solution would be acceptable if it represents better value for money than the credible alternatives. To examine this case, comparisons are once again made with the hydrogen solution, BB-EV having been dismissed on environmental grounds.

The relative merits of the ERS-BEV solution versus the hydrogen solution have been studied based on comparisons with the diesel status quo. Would it be cheaper for government to build-out an ERS system and set electricity prices at the wires at levels which match socket prices in the depot (thus enabling ERS-BEV's to meet or beat the current diesel TCO's), or would it be cheaper for government to subsidise the purchase price of hydrogen to meet the same objective?

Considering first the ERS approach, the price of electricity at the wires is now constrained by the desire to keep the cost of operating ERS-BEV's at a level which is comparable to that of operating diesel vehicles. As a result, the opportunity to generate revenues from the sale of electricity is dramatically reduced and the NPV for the ERS system becomes negative for all reasonable combinations of operator practice and system utilisation.

If we now consider the alternative approach, the NPV associated with subsidising hydrogen at the point of purchase is also negative; it has a value that varies according to the prevailing price of hydrogen. Figure 7.3 shows the points of balance where the negative NPV for ERS equates to the negative NPV for subsidising hydrogen. These points occur in any particular year where the line showing the cost of construction crosses the line showing the price of hydrogen. In this calculation, it is assumed that the ERS infrastructure is built-out at a discount rate of 3%, this being representative of government-financed infrastructure projects.

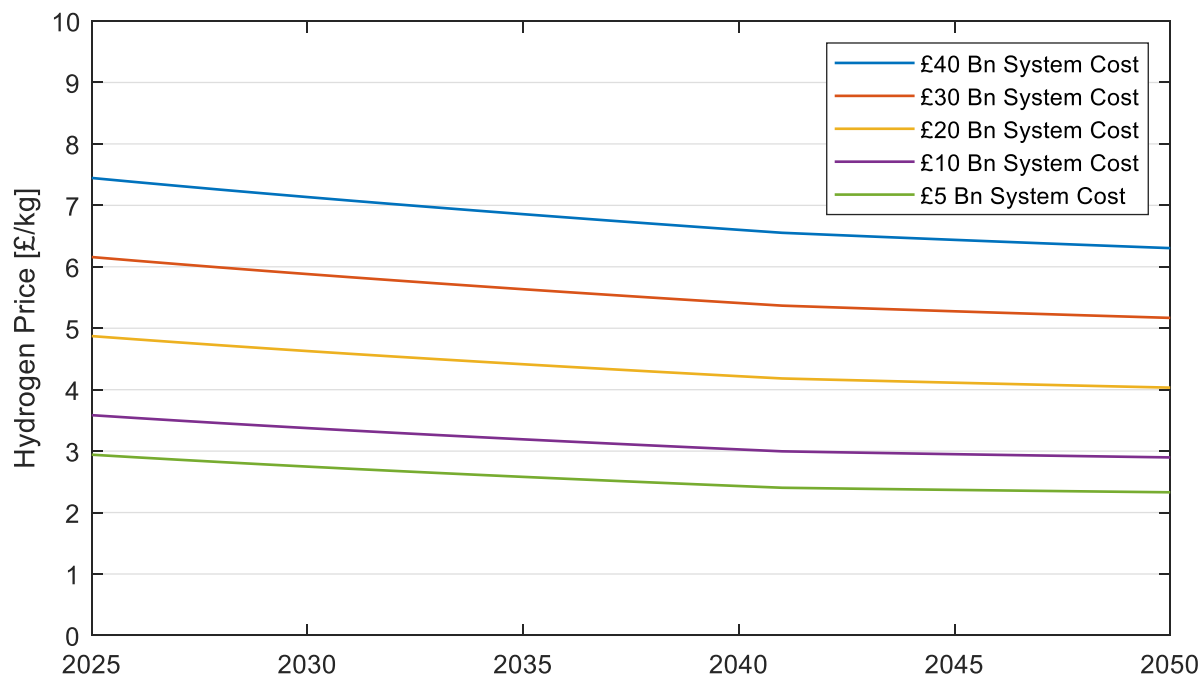


Figure 7.3: Government Intervention Scenario: The Balance of Cost at Different Points in Time for Subsidising the Supply of Hydrogen and Funding the Construction of an ERS Network.

At the low-power construction cost of around £15Bn - 20Bn in 2028 (start of build-out), the diagram shows that the cost to government of building the ERS matches the cost to government of subsidising hydrogen when the commercial cost of supplying hydrogen to the VFO's is in the range £4.30/kg - £4.80/kg. If hydrogen at this date is more expensive than this, the ERS solution will be the more attractive option for government to support and *vice-versa*. For most parts of the likely spectrum of prices for green hydrogen, therefore, ERS is likely to be the cheaper solution.

It should be noted that, on paper, the grey and blue hydrogen options look attractive, since they might very well cost less than £4.30/kg - £4.80/kg. But, following the arguments presented in Chapter 2, grey and blue hydrogen represent unacceptable solutions from an emissions perspective and should therefore be dismissed.

The case for 'Big Battery' (BB-EV) has also been examined. It is calculated that this solution is less costly in the Government Intervention scenario than either the ERS or the hydrogen solutions. In this case, there is a need for a minimal array of static charger sites (akin to the Phase 1 build-out for ERS enabled vehicles). These are needed to provide a level of confidence that vehicles will not be stranded if they run low on battery state-of-charge before completing a daily journey. In addition, the cost of a Big Battery lorry is significantly higher than that of its smaller battery counterpart, increasing the TCO and squeezing out the tax headroom available for ERS-enabled vehicles. This replaces the opportunity to raise tax with a need to provide a subsidy. The combination of providing an electricity subsidy to the VFO's and building-out the network of static charger sites is estimated to cost around £7Bn - £8Bn over the period 2025 – 2050. This compares with around £13Bn - £40Bn for the hydrogen solution (depending on the price of hydrogen) and £15Bn - £20Bn for the ERS solution.

As mentioned previously, the BB-EV solution has some significant environmental and operational drawbacks. In addition to this, the bigger batteries cause the business case to become more sensitive to the uncertainties in future battery prices than it is for ERS-enabled

vehicles. This increased sensitivity suggests that wider bounds should be put on the cost of the subsidies required, pushing the cost to government nearer to a figure of around £10Bn.

The BB-EV solution is not considered any further in this report. The possibility of adopting BB-EV's is, however, is an important possibility and this is an area which deserves more attention.

7.1.3 An Alternative Hybrid Funding Scenario

The case has been made in Section 7.1.1 that the infrastructure owner can return a good profit under the right circumstances. This possibility was dismissed, however, because the key risks were deemed to be too great for a private operator to make the initial investment.

This problem of unacceptable commercial risk could be circumvented if the government accepted responsibility for building-out the first phase of the ERS network and maintained the system until such time as enough ERS-enabled vehicles appear on the road to confirm the viability of the business model (probably around 2035). If the business model is seen to work at this stage, the system could be auctioned to a private company and the responsibility for implementing the DBOS Phase 2 upgrades and maintaining the system thereafter would rest with the new infrastructure owner. A preliminary examination of this model suggests that it would be profitable for a private company to step-in and purchase the system at a price that would represent a profitable return on the government's initial outlay and still leave room for commercial success as shown in Figures 7.4, 7.5 and 7.6. This is true even for the worst-case scenario in which the entire system is upgraded to 2MW/STK. These calculations have been done for a purchase price of £19Bn for three different return periods (2035 – 2050, 2060, and 2070, respectively). The NPV's look very attractive.

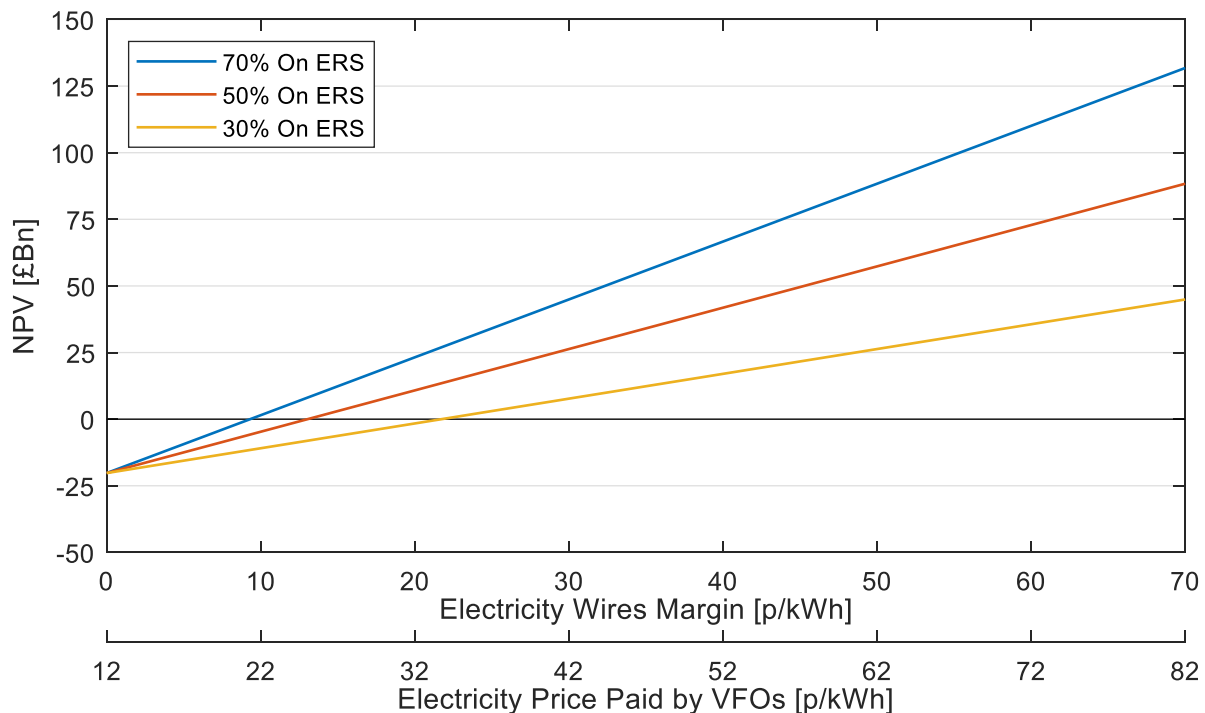


Figure 7.4: Hybrid Funding Scenario: NPV's over the period 2035-2050 for different levels of system utilisation.

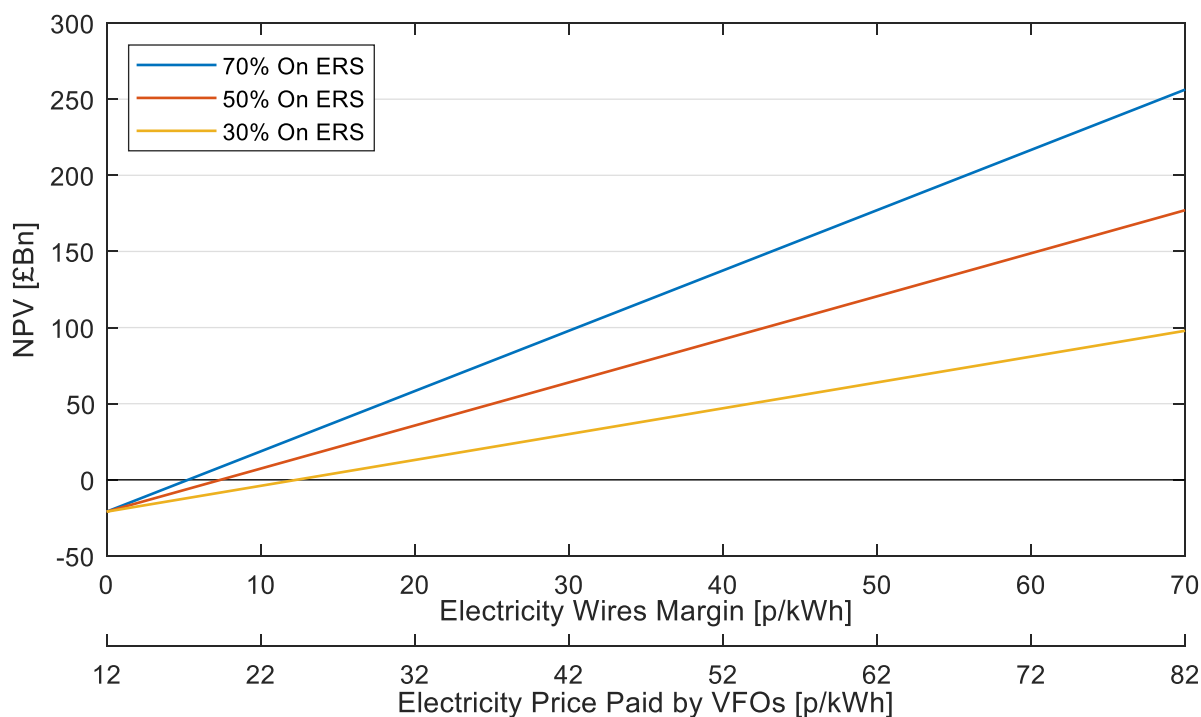


Figure 7.5: Hybrid Funding Scenario: NPV's over the period 2035-2060 for different levels of system utilisation.

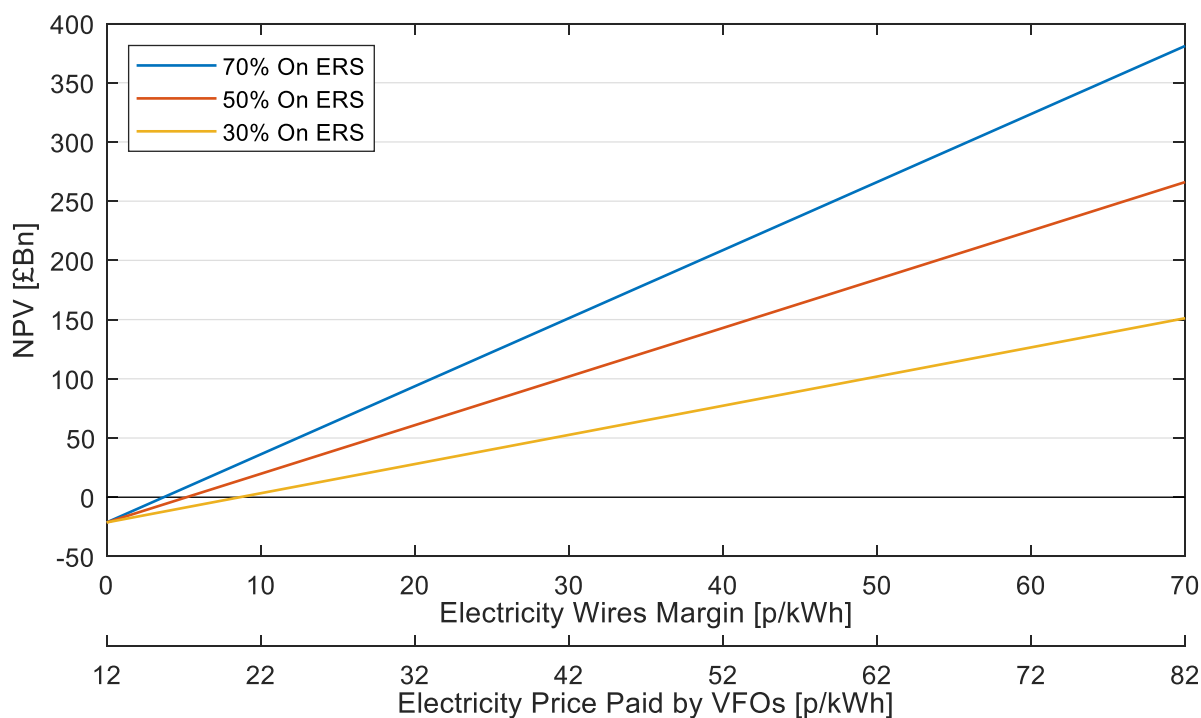


Figure 7.6: Hybrid Funding Scenario: NPV's over the period 2035-70 for different levels of system utilisation.

7.2 Environmental Metrics

7.2.1 Emissions in Use

Cumulative emissions over the period 2025 – 2050 were discussed in Chapter 2. Figure 7.5 below is reproduced here for the convenience of the reader.

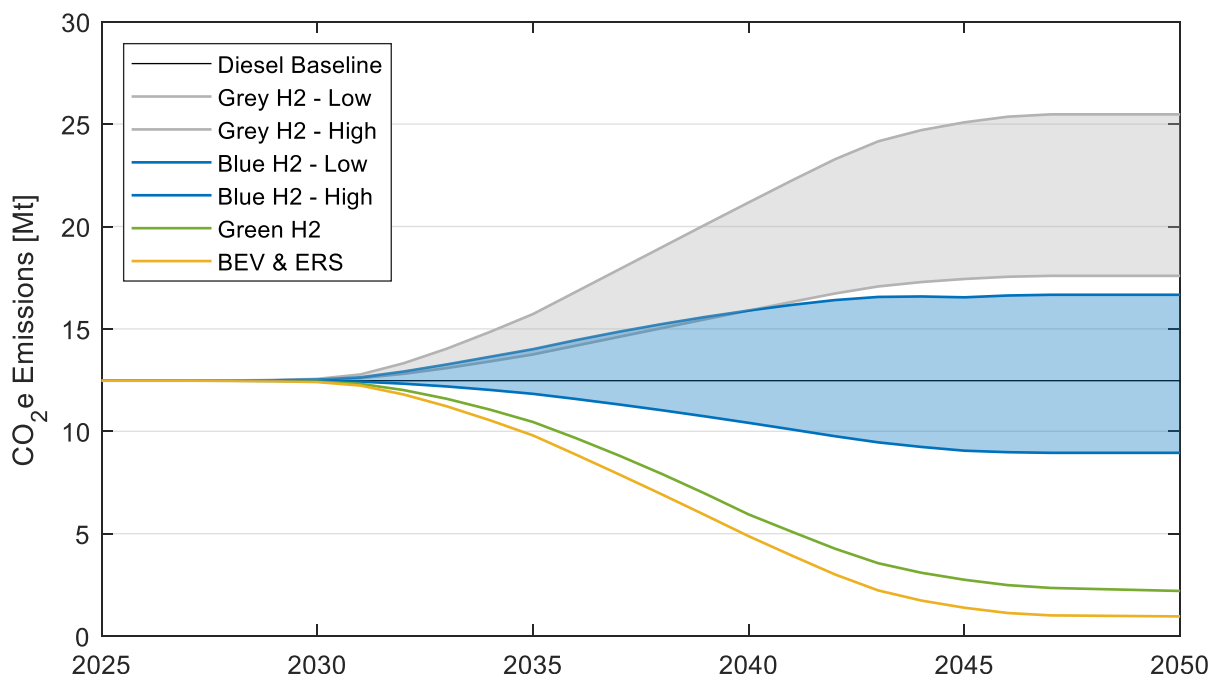


Figure 7.5: Predicted annual in use CO₂e emissions of HGVs for various technology solutions.

‘Emissions in Use’ represents the operational emissions of the heavy lorry fleet (some 200,000 vehicles over 25 t). These are generated principally by the combustion process for diesel-powered vehicles and by the emissions at power station sites for electric vehicles. For electric vehicles, the source emissions at the power stations are assumed to reduce to zero over a period of time in line with the 2050 emission reduction targets.

Total figures for GHG emissions in use over the period 2025 – 2050 have been calculated as shown in Appendix A using the market penetration rate for electric vehicles which was shown in Chapter 2 (Figure 2.1). At each year, it is assumed that the vehicle parc remains constant (approximately 200,000 vehicles) and that it comprises the calculated fraction of electric vehicles plus a balance of diesel vehicles. Figure 7.5 shows that attempting to achieve zero emissions via the grey or blue hydrogen pathways is not going to be successful. In the case of grey hydrogen, it would make things even worse than continuing with the diesel status quo.

The only transitional pathways which have the potential to meet the 2050 reduction targets are the green HFC -EV’s and BEV’s.

7.2.2 Embodied GHG’s (Vehicles)

An analysis of the embodied CO₂e emissions in the system has been conducted and is described in Appendix A. The biggest single sink for embodied CO₂e in an electric vehicle is the battery. In the calculations described in Appendix A, the carbon intensity for battery packs was taken to be 100 kgCO₂e/kWh. This is considered to be conservative. Using this figure, the total embodied CO₂e for the ICEV, HFC-EV (with a 70 kWh battery), and a range of BEVs (with battery sizes from 150 to 1,500 kWh) is shown in Figure 7.6. The battery is the largest

contributor from around 500 kWh and up, accounting for around three-quarters of the embodied carbon for the vehicle with a 1,500 kWh on-board battery.

In the case of hydrogen vehicles, the storage tanks are the biggest sinks for CO₂e due to the extensive use of energy-intensive carbon fibre. A 500 kWh BEV is approximately equal in embodied CO₂e terms to the HFC-EV in its assumed specification.

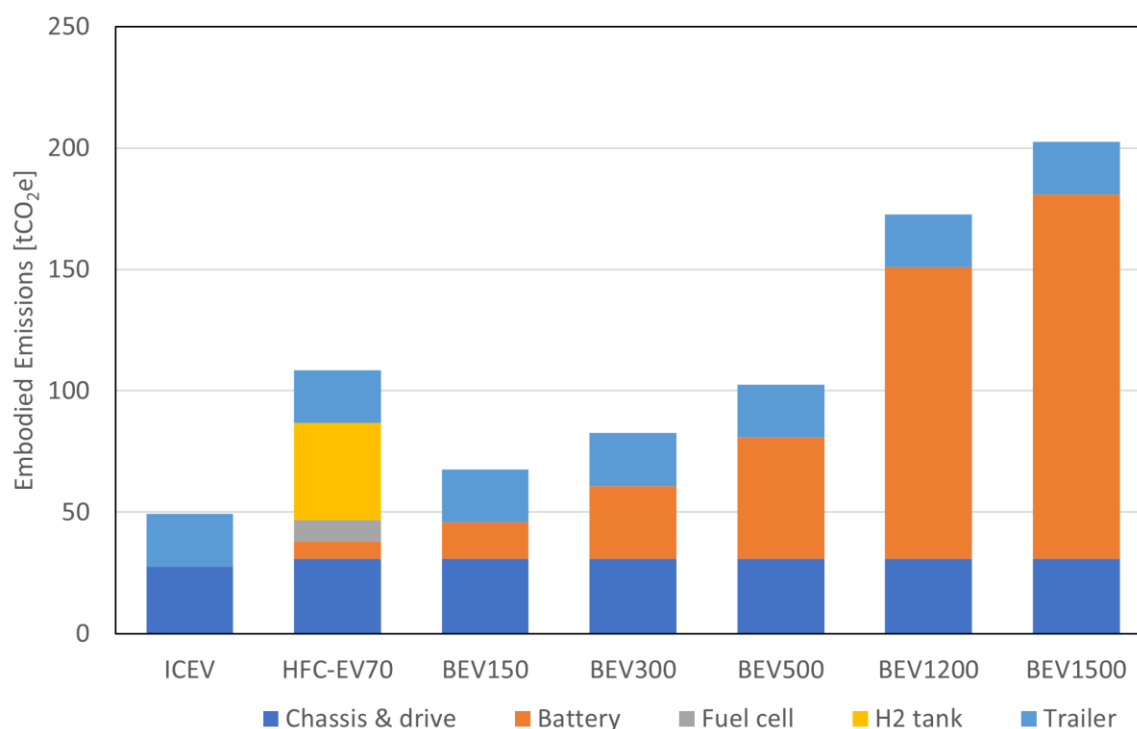


Figure 7.6: Estimated embodied carbon for a diesel ICE, HFC-EV, and BEVs with a range of battery sizes (44 t articulated vehicle combinations).

Case studies on the impact of battery sizing on embodied carbon are given in Appendix A which demonstrate the impact that ERS has on reducing the necessary battery sizes, and hence the embodied carbon in the vehicle fleet. The embodied CO₂e in a 500 kWh battery is approximately 50 tCO₂e. If each battery has a 6-8 year life, and each vehicle has a 12-15 year life, then each vehicle uses 2 batteries during its working life and accounts for 100 tCO₂e during that period. This takes the total embodied emissions per vehicle to around 160 tCO₂e. Making the appropriate allowance for the market penetration rate of electric vehicles, the total CO₂e embodied in the electric vehicle fleet over the period 2025-2050 sums to approximately 26 million tCO₂e (Table 7.3). The embodied emissions in a BB-EV (1,250 – 1,500 kWh battery) lies in the range 54 - 60 million tCO₂e per vehicle. This is far higher than the range of values for ERS-BEV's and it cancels out a significant fraction of the total CO₂e savings which result from the transition to BEV's.

7.2.3 Embodied GHG's (Infrastructure)

The embodied CO₂e emissions associated with the ERS infrastructure were calculated as shown in Appendix A using the design specifications and bills of materials available at the time of writing. In addition to the embodied emissions in the materials, some construction activity emissions were also incorporated. The basic ERS mast/cantilever design assumed in this study is shown in Figures 7.7 and 7.8. A mast spacing of 55 m and TPS substation spacing of 1 km were assumed.

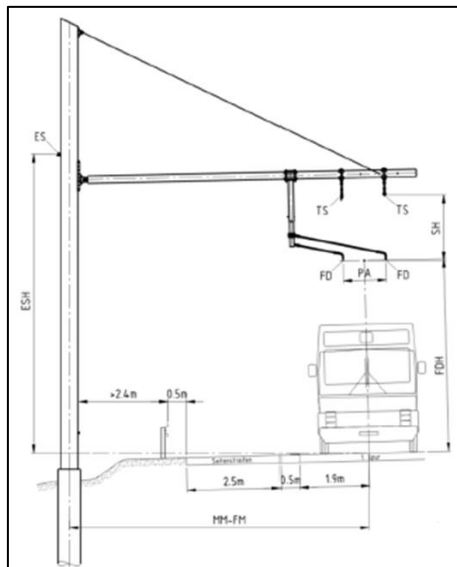


Figure 7.7: ERS mast design used to estimate embodied emissions.

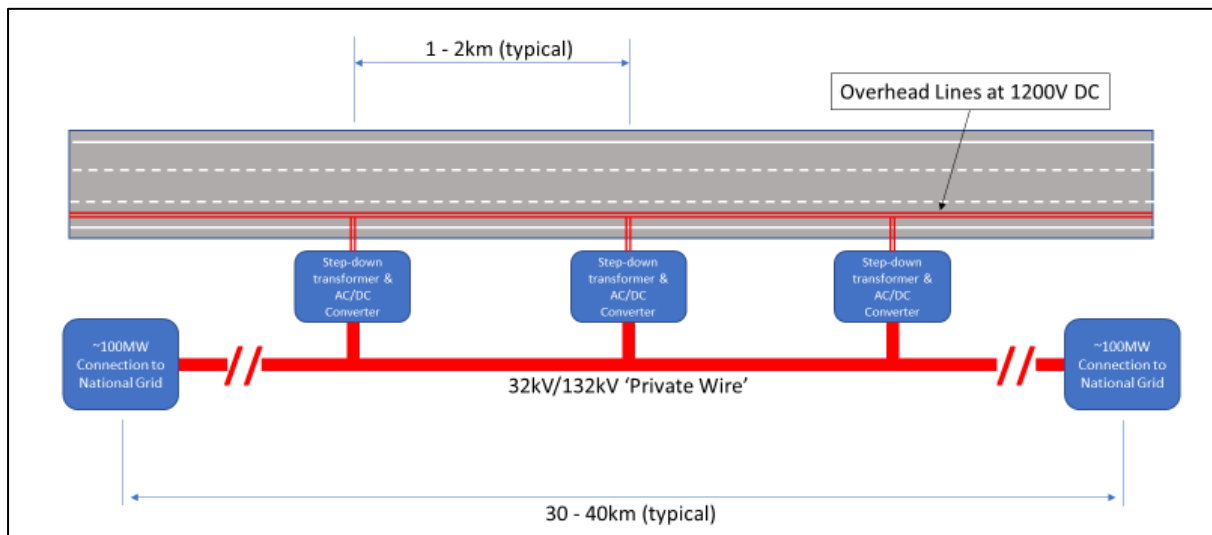


Figure 7.8: ERS power supply arrangement to estimate embodied emissions.

The total embodied CO₂e of the ERS was calculated to be 255 tCO₂e per lane-km. The breakdown is summarised in Table 7.1.

Component/Activity	Emissions [tCO ₂ e/lane-km]	% of Total
Masts	102	40%
Overhead lines	9	4%
Substations	28	11%
Private wires	6	2%
Concrete Crash barriers	101	40%
Disturbed soil	7	3%
Construction	2	<1%
TOTAL	255	

Table 7.1: Summary of estimated embodied CO₂e emissions for the ERS infrastructure.

Large public static charging sites were assumed to include a single 6 MW transformer connection to the grid, and 10 x 600 kW static chargers per site. The embodied carbon of the transformers was assumed to scale linearly with power capacity relative to the numbers calculated above, and the embodied carbon of the static chargers was assumed to be approximately equal to an equivalently sized transformer, linearly scaled from the above. It was further assumed that no major earth works would be necessary owing to the use of mostly existing refuelling sites and rest stops. It was hence calculated that each site incorporated 115 t of embodied CO₂e, as summarised in Table 7.2 below.

	Fraunhofer (6 MW) [tCO ₂ e]	Transformer [tCO ₂ e]	Chargers [tCO ₂ e]
Rated MW	6.0	6.0	0.60
Container	7.3	7.3	0.73
MV switchgear	7.8	7.8	0.78
Transformer	37.1	37.1	3.71
Rectifier	2.8	2.8	0.28
<i>Totals</i>	55	55	6
<i>Number per site</i>		1	10
<i>Totals</i>		55	60
Total per Site			115

Table 7.2: Estimated embodied emissions in static charging sites.

7.2.4 Aggregated Emissions Footprint (2025-2050)

A comparison of the aggregated figures for emissions in use and embodied emissions over the period 2025-2050 is made in Table 7.3 below. It can be seen that the embodied emissions are dominated by those associated with the vehicles (particularly the batteries), but these figures are much smaller than the emissions in use. In the relative scheme of things, the embodied emissions in the infrastructure are trivial.

	Emissions in Use [MtCO ₂ e]	Embedded Emissions in Vehicle and Charging Infrastructure [MtCO ₂ e]	
		Vehicle Base (500 kWh Battery)	Charging Infrastructure
Diesel 'Benchmark' Fleet	406	-	-
Electric Vehicle Fleet	182	26	-
ERS Light (5,500 STK)	-	-	1.4
Static Charging Network (2,100 Sites)	-	-	0.24
Net Saving/(Expenditure)	224	(26)	(1.64)
Net Benefit/(Disbenefit) over 25 years	~196 MtCO₂e		

Table 7.3: Summary of the cumulative in use and embodied emissions for the preferred ERS configuration (5,500 STK) from 2025 to 2050.

7.3 Social Metrics

The social benefits associated with the ERS solution revolve mainly around the creation of jobs. Over the near 20-year period of design and build-out, many thousands of workers will be needed in the fields of construction, materials supply, manufacturing, maintenance, and professional services. The employment profile will be:

- 7,000 – 8,000 site-workers over the period 2028 – 2032 (including specialists in the fields of TPS and OLE installations)
- 1,000 – 2,000 site-workers (mainly specialists in the fields of TPS and OLE installations) over the period of power upgrading (2035 – 2045)
- 500 - 1,000 manufacturing and materials supply chain workers over the period 2026 – 2045
- 500 - 1,000 professional services jobs in the fields of design, accountancy, project management, etc., for the duration of the design and build out activities (2026 – 2045)

All of these jobs will generate room for additional jobs in higher education and in training for the trades and other skilled staff.

7.4 Government Policies

All three aspects of the Business Case presented above are highly dependent on government policy. The most obvious of these is the government commitment to achieving the 2050 climate goals. Without this, nothing will change because the financial business case alone is not strong enough to initiate the transition to zero emission vehicles.

Other government/agency policies could also have a significant effect on the business case for building an ERS system. Some of these are summarised below.

7.4.1 Grid Connection Charges

Current practice is that significant new connections to the grid have to be paid for by the connection applicant. The cost of connection is calculated by the network operator (either the

DNO or the TNO) on a case-by-case basis. This is a very opaque process and the costs generated by the DNO/TNO are variable and difficult to predict. Examples of the allowances for grid connections which have been included in this study are shown in the table below (see also Appendices C and F).

Item	Construction/Installation Cost (inc. Grid Connection Charge)	Grid Connection Charge	Comment
ERS Network (2 MW/STK)	£4Mn/STK	£400,000/STK	Assumes TNO connections
ERS Network (0.5 MW/STK)	£2.9Mn/STK	£100,000/STK	Assumes TNO connections
Large Static Charger Site	£3.4Mn	£650,000	Assumes DNO connections at convenient locations
Small Static Charger Site	£1Mn	£250,000	Assumes DNO connections at convenient locations
Typical overnight depot (100 vehicles)	£5Mn	£3Mn	Assumes DNO connections at inconvenient locations

Table 7.4: Summary of grid connection charges for different types of charger installation.

There is a good case for arguing that the cost of making new connections should be socialised across all network users by adjusting the Network Use of Service charges. This proposition is under active consideration at the time of writing. If it is implemented, the cost of making grid connections when installing charging infrastructure would be reduced to zero with consequent benefits to the business cases for the vehicle fleet operators and the ERS/static charger developer/operators. This possibility makes the case for ERS under the ‘Government Intervention’ scenario and the ‘Free Enterprise’ scenario look stronger.

7.4.2 Electricity Levies

It has been assumed throughout the financial analyses presented here that the wholesale generation price of electricity is 5 p/kWh and the bulk user retail price of electricity is 12 p/kWh. The bulk user retail price includes a number of centrally-applied levies which are excluded from the wholesale price. These are:

- Feed-In Tariff
- Renewables Obligation
- Climate Change Levy

Together, these levies sum to around 4 p/kWh (a considerable fraction of 12 p/kWh). They are associated with the need to decarbonise the energy sector but, illogically, they are not applied to gas prices. This puts electricity at a disadvantage when it comes to switching to zero emissions energy sources and there is a good case for re-distributing the levies to avoid distorting the transitional pathway to 2050. The possibility of re-distributing these green energy levies in this way makes the case for ERS under the ‘Government Intervention’ scenario and the ‘Free Enterprise’ scenario look stronger.

8. Project Funding

Critical to the financing of ERS is the mitigation of a range of risks which, if not satisfactorily managed, will limit the opportunities for private investment. This chapter presents a summary of a number of the major risks that will be encountered in the delivery of the project. Risks which are described, and which investors will be very keen to understand, include utilisation, technology, revenue, grid capacity, delivery cost overruns, disruption to other users, uninsurable risks and project scale. Background detail may be found in Appendix H.

Government involvement will be essential to cope with some of the uninsurable risks and in particular to de-risk a funding gap during early construction and a difficult-to-predict, early utilisation phase as HGVs switch from diesel to electric in a merchant risk environment. The extent of Government involvement is dependent on whether a commercial environment can be created in which private investors are comfortable with the risk profile of the project. At one end of the scale we see a purely public sector solution (the Government Intervention Scenario) and at the other a model which allows private ownership and investment (the 'Free Market' scenario). In between is a range of different models, one of which is for the government to take an early lead to de-risk the business model before auctioning-off the system to private enterprise (the 'Hybrid Scenario').

With regard to fund-raising on the financial markets, a significant advantage of this project is that it can be designed and delivered in a manner which meets best environmental, social and governance practices (ESGs). It also clearly aligns with several of the UN's sustainable development goals (SDGs).

As an indication of what a successful privately funded project can look like the Thames Tideway Tunnel (TTT) model provides a useful example. This model has a capital value of around £4 billion financed through a 2:1 debt:equity ratio with a Government backstop covering the uninsurable risks. This is a very successful example of a model in which government de-risks the project so that private enterprise can provide the finance. Alternatively, there are other public sector models for national infrastructure such as National Highways and Network Rail which could equally be seen as models for the long-term delivery, ownership, operation and maintenance of ERS.

As part of any further studies of the ERS solution, at least three primary options should be considered:

1. Public sector body (most likely National Highways) to construct and operate ERS.
2. Regulated private sector utility, along the lines of TTT, with a Government backed insurance package.
3. Hybrid - for example government funds the construction and runs via HE until 2035 at which point it is auctioned off to a private investor who then takes over responsibility for the subsequent power upgrade phase of construction and system operation thereafter.

9. Stakeholder Engagement

Building a national ERS system will affect all parts of the UK. A large number of people, companies, organisations, and public bodies will need to be engaged in the debates about planning, design, and implementation. The delivery programme will have a very high public profile, particularly if the build timetable is as aggressive as has been suggested in Chapter 6. This chapter describes the stakeholder engagement activities which will be vital if a national ERS system is to be rolled out successfully.

9.1 Overview

The purpose of the work conducted here was to gauge the opinions and understand the concerns of a wide range of people and interest groups. The work was conducted in the South Humberside area which has been used as a proxy for national engagement because of the work being conducted on the M180 Demonstrator Programme in other parts of this project.

During the study, it has been found that there is an overwhelming sense that climate change is real and needs to be addressed. Diesel lorries make a high-profile contribution to the UK's greenhouse gas emissions and, in general, the ERS concept was well received by a wide range of different stakeholders. Different participants and groups, however, did express different concerns. The stakeholder groups were segmented as presented in Figure 9.1.

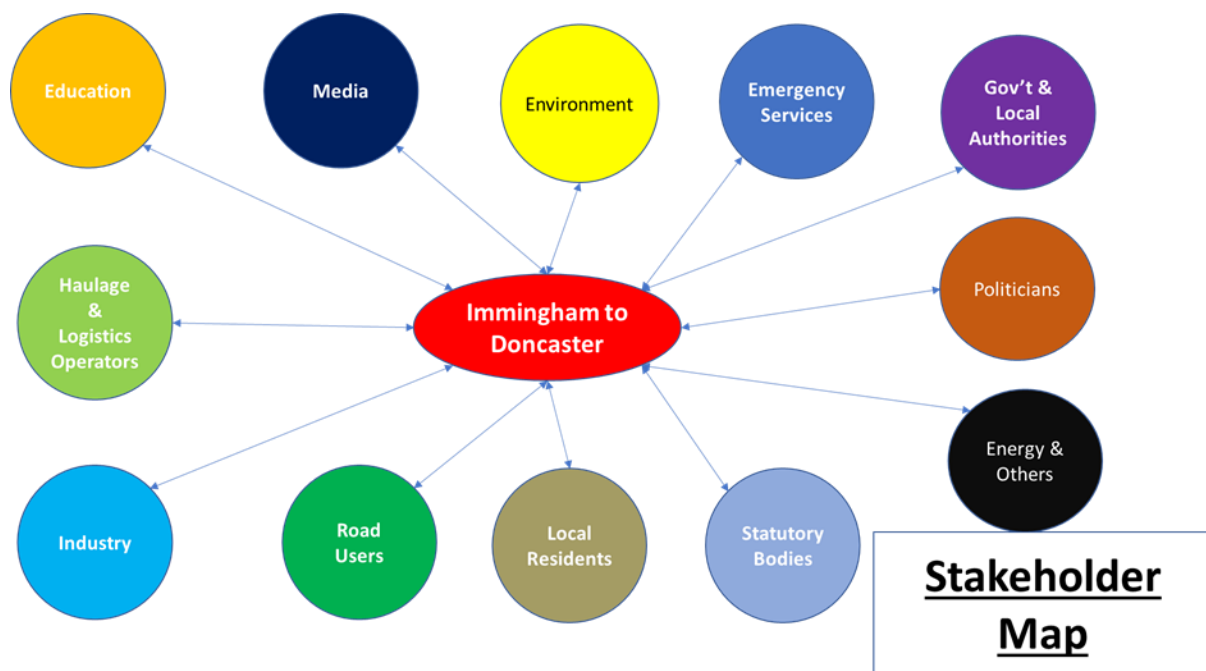


Figure 9.1: Stakeholder map.

Around 100 organisations have been contacted to understand their opinions. The methodology was as follows:

- One to one, mainly virtual, interviews.
- COP26: Scania Conference; Senior Management Presentation & Green Zone Stands.
- Operators Workshop on 24 January 2022.
- Doncaster Business Event on 4 February 2022.
- North Lincolnshire Focus Group on 4 February 2022.

The meetings typically served to update and inform stakeholders of the current position of the feasibility study which leads first into questions of clarification and later into some opinions. Meetings conclude with a request for three areas of concern or subject areas to be developed. By the end of the study period, most areas were covered although the Education and Politician categories were a little light. These insights were reinforced by the CPC Report in September 2020. The map, above, is conspicuous by the absence of one key stakeholder – National Highways. This account was handled outside this programme through a series of monthly liaison meetings. The full report may be found in Appendix I.

9.2 Common Questions

The following themes with questions were pursued by stakeholders:

Future Demands & Strategy:

- What is the demand for 44 t lorries in 2040 and beyond?
- Will the consumer demands be the same in 2040 and beyond?
- How does Freight Decarbonisation tie in with DfT's overall strategy and other government ones e.g. energy?
- What will the policies and incentives be to encourage take up of ERS? (COP26)

Disruption:

- What disruption will there be during construction?
- What disruption will be caused by HGVs running out of battery power?
- What happens when there is planned maintenance to the inner lane?
- What is the impact of ERS on SMART motorways?
- What is the resilience of the system e.g. what happens if a length of motorway is closed longer than the battery range?
- Where will the detours run?

Logistics & Operations:

- What is the impact on operations?
- What happens to availability during incidents and planned maintenance?
- Will operations have to change to accommodate charging times?
- Will more vehicles be needed?
- How will the weight of the battery affect the payload?
- How does the transition period work?
- How does the whole life cost of a vehicle compare with a diesel lorry?

Carbon:

- Does Freight Decarbonisation offer the best bang for the carbon buck?
- What is the embodied carbon of the system?
- How does ERS compare with other technologies?

Financing of the Infrastructure:

- How will it be financed?
- What is the role of the private sector?
- Who is paying for it (the user or the tax payer)?

Asset Ownership:

- Who owns the infrastructure asset?
- Who maintains it?

Safety:

- What happens if the overhead lines come down?
- How are the overhead lines disconnected to allow for emergency services to operate safely under them?

Power:

- What are the static charging options?
- What is the impact on generation and transmission?
- What is the range of a battery?
- How long before a 1MW super charger is available?
- Can the system cope with a queue of lorries starting off simultaneously after an incident?
- How can local sources of renewable energy be captured?

Roll Out Programme and Budget:

- How will the supply chain deliver such an ambitious programme in terms of time and cost?

9.3 Key Stakeholders

National Highways represents the major stakeholder. Unlike other technologies, ERS, using overhead lines, introduces a secondary asset to its highway network. Therefore, there are obvious concerns over ownership, safety and maintenance. The team has met it on a regular basis throughout the study. New roads schemes are dependent upon the “buy-in” of the Haulage and Logistics operators. Their business models are based on the flexibility afforded by diesel. Many operate on a 24/7 basis and a single lorry undertakes a mix of journeys rather than a dedicated route or shuttle. Concerns were expressed about whole life costs and any potential reduction in payload caused by the weight of a battery. The Haulage and Logistics sector is roughly divided into 20% who are committed to change; 60% who are waiting to see which way the market will go; 20% who are sceptical. The sector has a long tail of small family owned businesses. Between 2022 and 2040 (when diesel lorries will no longer be for sale) there will be 4 to 5 buy and sell lorry cycles. Therefore, for businesses, which are more concerned about surviving the year, ERS development is not relevant. The initial “buy-in” is going to come from the 20% early adopters. These are corporates which have an environmental policy and have pressure from investors and customers to change.

9.4 Environment

The Environment Agency sees Climate Change as needing immediate action and has adopted the mantra of “Adapt or Die”. Habitats will be a concern and this was trailed by Baroness Brown of Cambridge (Julia King) at COP26. Interestingly, visual impact did not feature very strongly until one of the last meetings. National Highways made a telling point that all motorway furniture and features are painted a specific brown colour between J28 and J29a on the M1 to meet the sensitivities of local heritage and tourist attractions.

9.5 COP26

COP26 was encouraging and emerging were five key messages:

- Replacing diesel lorries with ERS is doable.
- Collaboration of all interested parties is needed.
- Policy and incentives will be needed to allow planning with certainty.
- Demands on the Fleet will change over the next 20 years – diesel/transition/steady state.
- Clear plans needed for the investment in infrastructure that provide confidence.

9.6 Clear Government Policies and Incentives

COP26 gave a clear signal to the country and to the world that there was a swell of opinion and momentum to effect change and therefore meet the 2050 Net Zero targets. One of the key themes coming from COP26 events and the logistics and haulage operators' workshop is the need for clear government policies including incentives to encourage early adopters and to enable investment in the infrastructure.

9.7 White Elephants and Bang for the Buck

Proceeding with ERS will be a political decision. Government advisers have concerns over the cost and whether the large capital investment will be overtaken by changing and emerging technology. The more radical would like to see a fresh approach to how the UK transports goods around the country. There is an in-built belief that rail can solve this which does not take into consideration the lack of capacity on the current system.

Nevertheless, any investment needs to be justified over its full life. A decision today needs to be still relevant in 2060. An illustrative figure of £20Bn was used for the capital investment required to roll out ERS. This caused concerns of whether it would be overtaken by new technology, changing transport and/or changing consumer patterns. Any one or more of these would render the scheme obsolete and therefore create a “white elephant”.

Others wanted reassurance that with limited funds, ERS would represent value for money. Relative to other greenhouse gas contributors e.g. steel and cement manufacture, is ERS the priority? In other words, they wanted to maximise the Carbon “Bang for the Buck”.

10. Conclusions and Recommendations

The UK faces a considerable challenge if it is to meet the 2050 net-zero emission target for heavy road freight. A good start on zero emissions technology has been made by the automotive industry where battery-electric vehicles are fast becoming established as the preferred way forward. Unfortunately, this success does not translate easily into the long-haul heavy-vehicle sector where the loads hauled and the distances travelled require very large amounts of traction energy to be stored on-board the vehicles. This amount of energy is not easily stored in a battery and alternative solutions need to be studied.

One possible alternative to pure battery-powered vehicles is to introduce an 'electric road system' (ERS) along all the main routes on the Strategic Road Network. This would provide charge-on-the-move, via a pantograph, to otherwise conventional battery-powered vehicles, enabling them to have an operating range which is limited only by the length of the ERS. This means that vehicles with quite small batteries could reach almost anywhere in the country, simultaneously removing both range concern and the cost of each vehicle.

This report has examined the details of this proposition and assessed the benefits and dis-benefits which might arise. Comparisons have been made with the credible alternatives. It has been found that the advantage is more likely to lie with the ERS solution than either of the two principal alternatives (namely a pure battery approach and a hydrogen approach).

10.1 Conclusions

The key findings of this report are:

- Simulations of a range of different ERS system configurations suggest that a relatively short length of electrified roads (in the order of 5,500 km), augmented by a national network of static charging stations (up to 2,100 distributed across the nation) would meet the needs of the UK logistics industry.
- The ERS core technology is established and has been proven to work. Demonstration programmes in Sweden and Germany have shown that the technical concept is sound.
- A Preferred System' has been defined which is sufficient to test the technical and economic feasibility of building an ERS system in the UK.
- There is currently a wide range of uncertainty associated with the cost of delivering ERS and its alternative solutions ('Big-Battery' and hydrogen). Nevertheless, the outline performance specification and system design put forward in this report suggest that, for most parts of the likely operating envelope, ERS will represent the best combination of emissions reduction, technical risk, and low cost.
- The Preferred System which has been put forward would enable the vehicle fleet operators to serve all of today's operational requirements without increasing the fleet size or increasing the working day by more than 15% in the worst case. (The average working day would be extended by less than 0.5%).
- Several key difficulties are highlighted, including the need to build-out the first phase of the system (5,500STK) and achieve operational status by 2032. Whilst there appears to be no intrinsic reason why this cannot be done, it nevertheless represents a 3x increase over the UK historic delivery rate for rail electrification programmes. This target creates a serious challenge from the construction delivery perspective.
- The aggressive construction timetable highlights the much more general need for UK construction programmes to be foreshortened if the nation is to meet its 2050 Net Zero targets. This wider need is driven by the imperative to build a very large amount of new power generation and transmission/distribution capacity. In national terms, this is a

much bigger issue than heavy road freight. A change of gear of this magnitude could require, amongst other things, big changes to the way in which major projects/programmes are procured in future.

It is concluded that a national ERS system has a number of operational attractions and has a potential cost advantage over the alternative solutions. Such a system requires an up-front investment by government or private enterprise but, in this respect, it is no different from the hydrogen solution.

It is worth noting that an ERS system is unlikely to ever become a stranded asset because it will have utility even in the event that hydrogen vehicles become the preferred norm. This is because most hydrogen vehicles have electric powertrains and it will always be more energy-efficient for hydrogen vehicles operating on ERS-enabled roads to draw power from the wires via a pantograph than it will be to purchase hydrogen from commercial sources.

In summary, the high-level case for ERS has been explored and a positive position has been established. It is clear that ERS is a promising approach, but there remain many practical and detailed issues which need further attention before a national ERS development project can be implemented. These are outlined in Section 10.2 below.

10.2 Recommendations for Further Work

Key issues requiring further study are summarised below. Some of these issues will require considerable effort. It is recommended that a programme of work designed to address them is launched immediately without waiting for the launch of the Demonstration Programme on the M180.

10.2.1 Costing and Finance

- 1) Understanding the cost-base for installing a national ERS system needs further work. Figures of £2.9Mn/STK for a low-power system and £4Mn/STK for a high-power system have been calculated, but there are (inevitably) some significant uncertainties in these estimates. For example, some baseline costs were examined from previous work in Germany and Sweden and the comparable UK costs were found to be significantly higher. A highly-focused cost benchmarking exercise is required if a definitive set of construction cost estimates is to be produced.
- 2) The cost-bases for the alternative technology solutions set the benchmarks for ERS when considering the best value for money. Understanding these alternative costs is extremely important. In this study, the future price of green hydrogen as supplied to the vehicle fleet operators in 2035 has been taken to lie in the range £3.80/kg - £6.90/kg. This very wide range introduces uncertainty in the cost comparisons and more rigorous study is required if this problem is to be properly addressed.
- 3) The business case modelling presented in this report needs to be extended and adjusted to include a more comprehensive model of demand and include the improved cost-base information referred to in (1) and (2) above.
- 4) The funding models within which the build-out of the ERS might be delivered could take many different forms. Three models have been explored in the preliminary assessments reported here but several more could also be explored. Further work is required in this area.

10.2.2 Technical

- 1) The specification of the power rating for the ERS across different parts of the national system has a significant effect on the cost of the system. An initial assessment of power requirements has been made based on assumed patterns of operation and assumed compositions of vehicle fleets. Figures of 0.5MW/STK and 2MW/STK have been developed for low and high-power systems (i.e. 'bookends' to the likely range of costs), but a more accurate statistical approach is required to produce robust specifications for the necessary power requirements. This might be done using stochastic agent-based simulation techniques.
- 2) There is a potential problem with low bridges/gantries (clearance height <5.2m above the carriageway). More than 200 of these structures exist on the strategic road network and, in the presence of double-deck trailers (which are in common use in the UK), it is not possible for the wires to pass continuously under these obstructions using currently available techniques (The wires therefore need to be terminated and re-started either side of the obstruction). An elegant general solution, which removes the need for terminating the overhead wires and lowering the pantograph at each low bridge, needs to be developed.
- 3) The constraints of traffic management impact the ability to build quickly. An installation method needs to be developed which maintains high levels of safety but reduces traffic disruption. In particular, it would be highly beneficial if the need to introduce temporary contraflows during the construction period could be eliminated.
- 4) Every aspect of the site-based construction process needs to be re-examined with a view to increasing the speed of installation and reducing cost. The roles of off-site construction and on-site automation should be central to this task.
- 5) A suitable approach to metering and billing needs to be devised for the purchase of electricity through the ERS system. This must include rigorous processes for meter verification and financial audit.
- 6) A comprehensive cyber-security strategy will need to be developed. This is a critical item – the consequences of an attack in which the national system is disabled would have an immediate effect on the population at large (empty shelves in the supermarkets, etc). An extended period of disablement would result in serious harm to society and the economy (manufacturing disruption, medical shortages, etc).

10.2.3 Safety, Standards, and Procurement Processes

- 1) A strategic approach to safety is required which leads to the development of formal Safety Cases for the construction and use of the ERS system and its associated static charging sites.
- 2) There will need to be comprehensive developments in the following areas before a national system can be fully specified.
 - National standards for the approval of overhead power lines on roads and traction power supply and other ERS-related equipment at the roadside.
 - International Standards to ensure interoperability with Continental Europe.
- 3) Major adjustments to the processes of procurement and delivery need to be explored, in particular the introduction of:

- Long term and secure client commitments (a so-called 'Programme Approach'). This will be necessary so that the contractors who build the system can invest in the necessary skills, equipment, and practices which are required to transform current norms.
- Well-funded programmes of skills training and capacity building in the relevant supply chains.

10.2.4 Stakeholder Engagement

1) A programme designed to engage vital non-industry stakeholders in the debate about ERS needs to be planned and implemented. Stakeholder groups in this category include national government and its agencies, local government, environmental lobby groups, local interest groups, prominent influencers, etc. The programme should address:

- Technology readiness
- Carbon footprint
- Energy efficiency
- Operational performance
- Cost

2) The larger corporate haulage and logistics companies should be embraced in order to deliver a logistics strategy based on the adoption of ERS. This must include provisions for the transition phase during the late 20's and early 30's. This activity should include the formation of a working group of senior industry people who can work together to represent the interests of the many and diverse types of vehicle fleet operators.

3) A more focused group of government departments and agencies needs to be engaged on matters of technical and economic policy. This group of stakeholders includes DfT and National Highways (for system construction and operation), National Grid and the District Network Operators (for connections to the electricity supply networks), Ofgem (for electricity pricing and levies)

4) The need to define and communicate the best pathway to zero emissions heavy road freight operations is paramount. Materials must be prepared which compare the costs/carbon-impacts of ERS and provide examples which address the concerns and enthusiasms of local interest groups. Examples include:

- The place of local sources of renewable energy in the development of future construction and operational plans.
- The development of a 'ribbon of excellence' along M180 to service ERS involving the construction industry, offshore wind, and other industry groups. This could be based around the proposed Freeport at Immingham, British Steel at Scunthorpe, Siemens Gamesa at Hull, and the logistics hub at Doncaster.

5) The M180 Demonstration Project should be used to maximum effect. A visitor centre should be created and used to encourage interest and participation in the development of a national ERS solution.

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Appendix A – GHG Data and Analysis

In this appendix, the in use and embodied CO₂e emissions for the different technology solutions are calculated over the period 2025 – 2050 for the ‘Heavy Vehicle’ segment of the UK HGV parc (rigid and articulated lorries >25 t GCW; approx. 200,000 vehicles). We then also consider the embodied CO₂e emissions from both the vehicles and infrastructure.

A.1 Hydrogen Calculations

In the UK, both grey and blue hydrogen are produced predominantly by steam methane reformation (SMR). The GHG content of both forms includes the fugitive methane from the upstream chemical feedstock (natural gas) plus the downstream emissions of the process itself. Downstream CO₂e emissions from the SMR process are well understood, but few researchers have reported on upstream fugitive methane emissions. This therefore represents an area of considerable uncertainty regarding grey hydrogen emission intensities.

The uncertainty is even greater for blue hydrogen. Since there are no examples anywhere in the world of blue hydrogen production facilities which operate at large scale and have long historical data records, all estimates for the GHG intensities of blue hydrogen have to be based on calculation.

Theoretical estimates for the GHG intensities of grey and blue hydrogen are critically dependent on the assumptions which are made about process efficiencies. These principally relate to accounting for fugitive methane emissions from the upstream natural gas chemical feedstock and the performance of the carbon capture equipment which is fitted to the flue stacks of the reformer and its heaters. The basis for these assumptions in the work reported here has been taken from the work of Howarth & Jacobson (2021). Table A.1 show the upper and lower estimates for grey/blue hydrogen production which have been taken in this study and their relationship to the ‘baseline’ results presented by Howarth & Jacobson (2021).

Methane Leakage Rate	Grey Hydrogen Emissions (Global Warming Potential) [kgCO ₂ e/kgH ₂]			Blue Hydrogen Emissions (Global Warming Potential) [kgCO ₂ e/kgH ₂]		
	(34)	(86)	(105)	(34)	(86)	(105)
0%	9.00			3.60		
1.54%	10.68			6.36		
2.54%		15.96			13.08	
3.50%		18.36			16.20	
4.30%						

Table A.1: Emission intensities of grey and blue hydrogen, with the selected low and high values used in this study (baseline values from Howarth & Jacobson (2020) in orange).

A.1.1 Grey Hydrogen

From Table A.1, the average SMR GHG intensity for the production of grey hydrogen lies within the range of 10.68 – 15.96 kgCO₂e/kgH₂, with an average of 13.32 kgCO₂e/kgH₂ (mature technology unchanging with time). The incremental addition for purification, compression, transport, and storage/dispensation is 1.1 kgCO₂e/kgH₂. The average intensity ‘at the pump’ is 14.42 kgCO₂e/kgH₂.

A.1.2 Blue Hydrogen

From Table A.1, we assume GHG intensity lies in the range 6.36 – 13.08 kgCO₂e/kgH₂ and the capture rate improves with time according to the graph below.

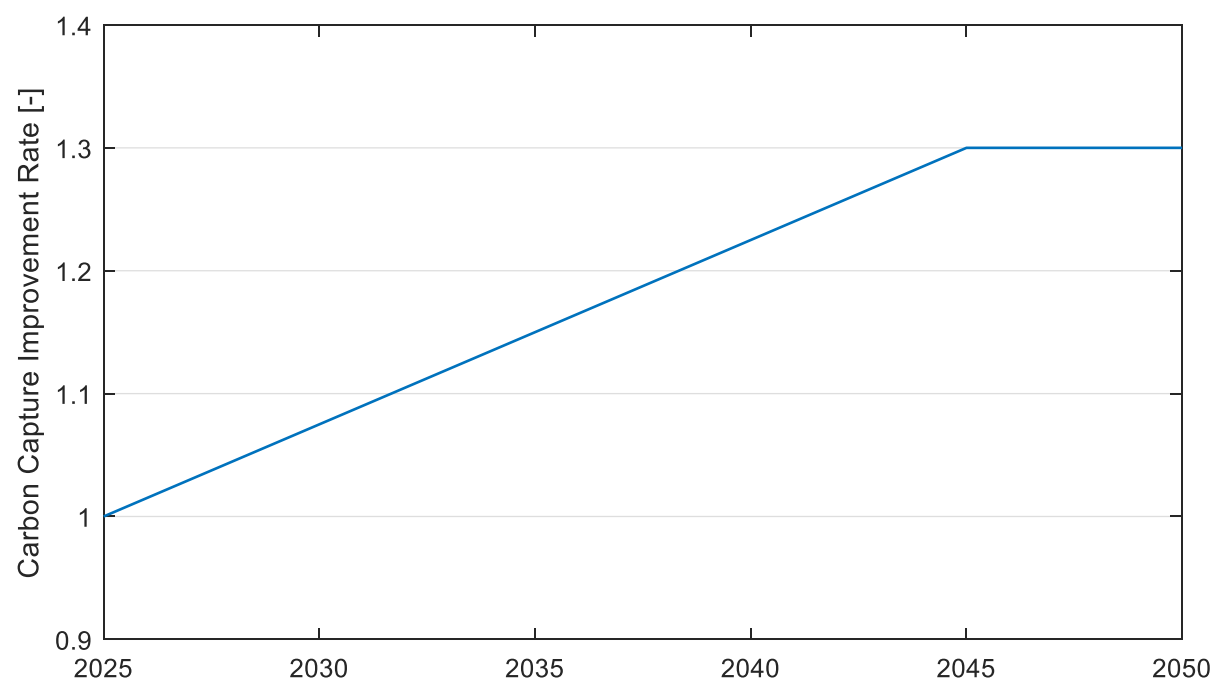


Figure A.1: Carbon capture improvement rate over time for blue hydrogen.

A.1.3 Green Hydrogen

We assume electrolysis via alkaline electrolyzers that improves over time as shown in Figure A.2. We also assume that grid electricity is decarbonised over time as shown in Figure A.3.

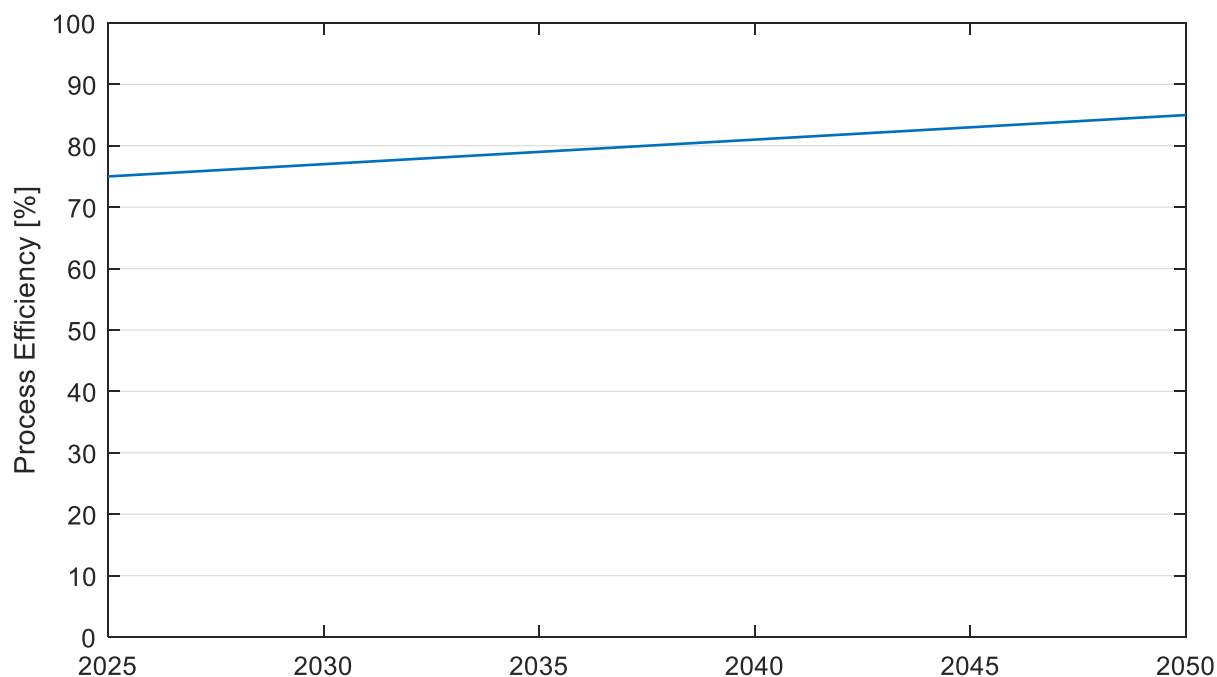


Figure A.2: Process efficiency for green hydrogen produced via alkaline electrolysis.

A.1.4 UK Grid CO₂e Intensity

For hydrogen produced via electrolysis and the battery/ERS vehicles, the UK grid is decarbonised according to Figure A.3.

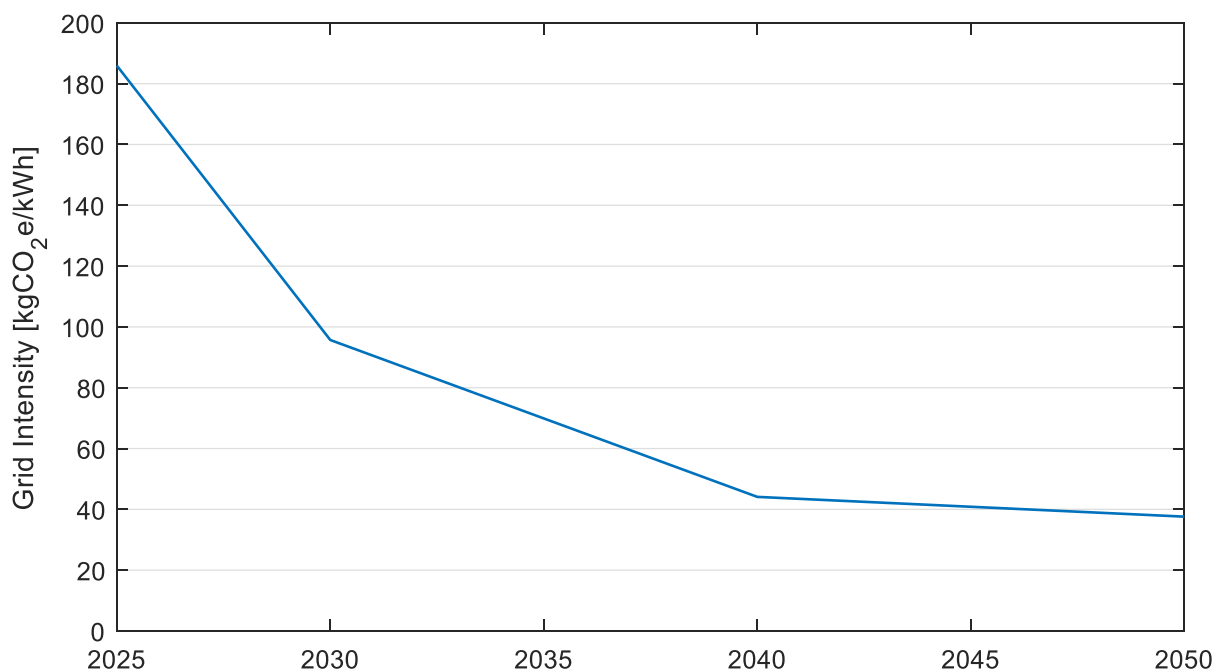


Figure A.3: Grid CO₂e intensity from 2025-2050, from Hill and Amaral (2021).

A.1.5 Vehicle Parc Calculations

We assume that new vehicle annual sales are 8.5% of vehicle parc, and the % share of that market for zero emission vehicles grows as shown in the table and graph below. We assume that no diesel vehicles are purchased after 2035.

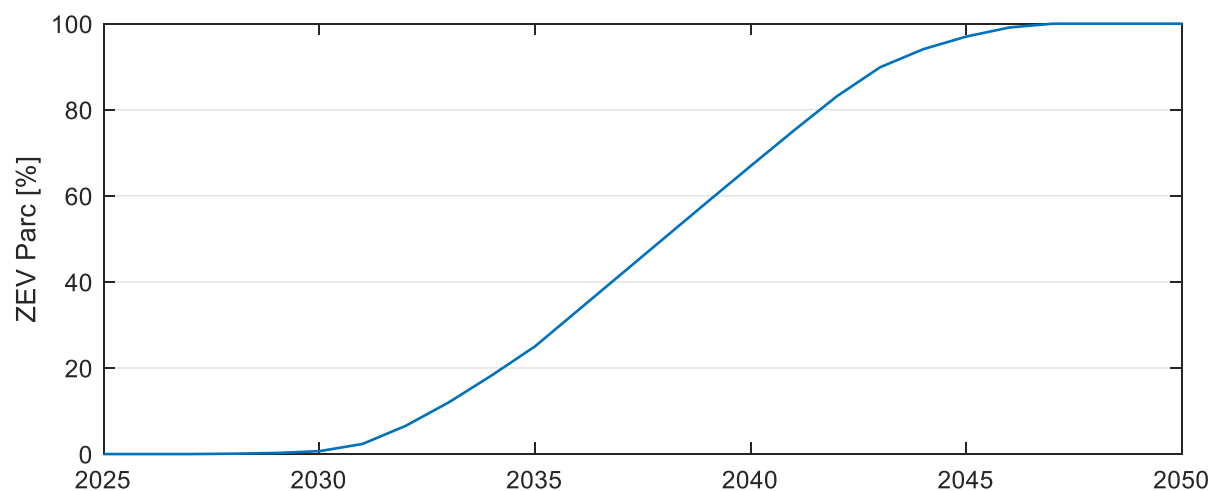


Figure A.4: Assumed uptake of ZEVs across 2025-2050, as a percentage of the total UK HGV parc.

A.2 In-Use CO₂e Emissions

Based on the composition of the vehicle parc and the CO₂e intensity of using electricity/hydrogen as the energy vector, the annual and cumulative emissions associated with BEV/ERS, grey hydrogen, blue hydrogen, and green hydrogen are calculated, shown in Figures A.5 and A.6. The shaded areas on the diagram represent the region of uncertainty regarding the production of grey and blue hydrogen.

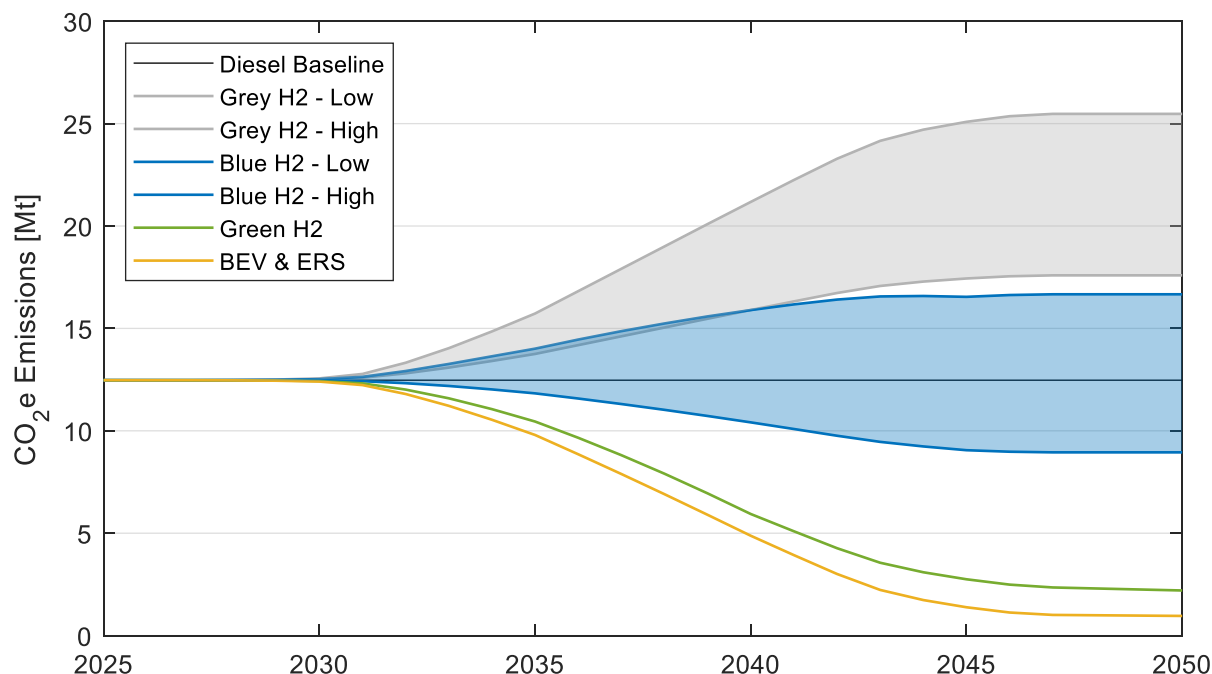


Figure A.5: Predicted annual in use CO₂e emissions of HGVs for various technology solutions.

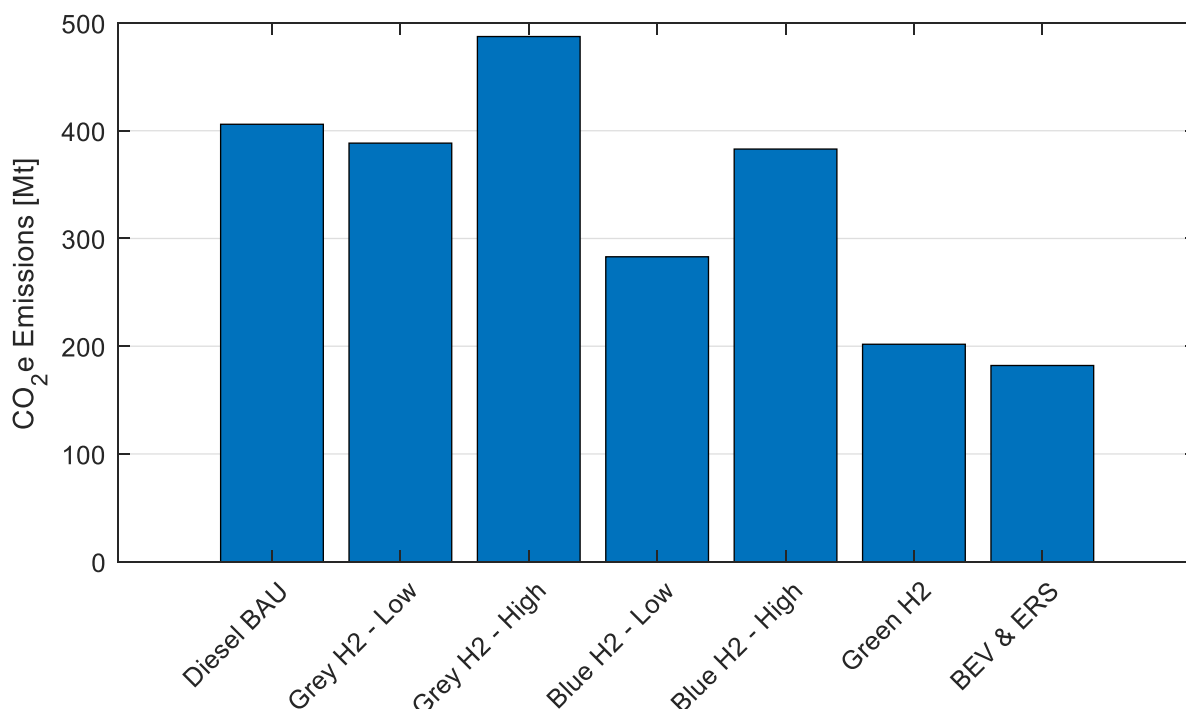


Figure A.6: Predicted total in use CO₂e emissions from 2025-2050 of HGVs for various technology solutions.

From these figures, the following conclusions can be drawn:

1. There are wide bands of uncertainty regarding the CO₂e intensities of both grey and blue hydrogen. Even under the most optimistic assumptions, grey hydrogen shows no significant improvement in CO₂e emissions over diesel fuel and blue hydrogen fails to provide a 'Zero Carbon' solution.
2. Under anything other than the most optimistic assumptions, grey hydrogen has a *worse* emissions footprint than diesel and the 'clean' properties of blue hydrogen are dramatically reduced.
3. Only Green Hydrogen comes close to the direct use of electricity in terms of providing a zero emissions solution (but does not reach direct electrification). Due to the inefficiency of the hydrogen cycle, it represents a more expensive solution (See Appendix C).

A.3 Embodied CO₂e Emissions

Embodied GHGs arise as a result of the processes of vehicle manufacturing and infrastructure construction. High-level estimates for each case are presented in the following sub-sections.

a) Vehicles

Vehicle embodied carbon was calculated for a diesel ICE vehicle, a BEV representing both full battery electric and ERS battery electric vehicles, and a HFC-EV. The starting point for the analysis was the life cycle analysis of diesel and battery electric lorries carried out by Scania in 2021 (Burul and Algesten, 2021). This provided an approximate bill of materials and embodied carbon for a 28 t ICE and 28 t BEV. The bills of materials were scaled up to represent equivalent 44 t vehicles in each case, assuming that the relative proportions of materials masses were maintained. For the case of the BEV, the battery contribution was removed, leaving only the chassis and drivetrain, so that the battery could be considered separately, and the impact of several battery sizes studied. The calculations are summarised in Tables A.2 and A.3 and yield 27.53 tCO₂e/vehicle (ICE) and 31.0 tCO₂e/vehicle (BEV without battery).

Bill of Materials	Estimated Mass [t]	Mass Share [%]	Estimated Emissions [tCO ₂ e]	Emissions Share [%]
Steel	5,130	57.0%	12.65	46%
Cast iron	1,980	22.0%	3.58	13%
Other metals	90	1.0%	1.38	5%
Aluminium	450	5.0%	2.20	8%
Electronics	9	0.1%	1.10	4%
Plastics	360	4.0%	1.65	6%
Copper	63	0.7%	0.28	1%
Other materials	180	2.0%	0.55	2%
Fluids	90	1.0%	0.08	0%
Elastomers (e.g. rubber)	630	7.0%	1.38	5%
Inbound logistics	-	-	2.48	9%
Assembly	-	-	0.22	1%
TOTAL	8,982 t	100%	27.53 tCO₂e	100%

Table A.2: Estimated embodied CO₂e emissions for a 44 t diesel lorry.

Bill of Materials	Estimated Mass [t]	Mass Share [%]	Estimated Emissions [tCO ₂ e]	Emissions Share [%]
Steel	4,800	48.0%	12.33	23%
Cast iron	1,800	18.0%	3.22	6%
Other metals	50	0.5%	1.61	3%
Aluminium	700	7.0%	3.75	7%
Electronics	10	0.1%	2.14	4%
Plastics	500	5.0%	2.14	4%
Copper	200	2.0%	1.07	2%
Other materials	200	2.0%	0.54	1%
Fluids	30	0.3%	0.05	0%
Elastomers (e.g. rubber)	500	5.0%	1.61	3%
Battery Cells (300 kWh)	1,300	13.0%	21.98	41%
Inbound logistics	-	-	2.14	4%
Assembly	-	-	0.21	0%
TOTAL	10,090 t	100%	52.80 tCO₂e	100%
TOTAL (NO BATTERY)	8,790 t	100%	31.00 tCO₂e	100%

Table A.3: Estimated embodied CO₂e emissions for a 44 t BEV lorry.

The embodied carbon in the base fuel cell electric vehicle (without Hydrogen tanks, fuel cell or battery) was assumed to be the same as that of the battery electric vehicle without the battery. The fuel cell, hydrogen fuel tanks and battery were then added separately. The HFC-EV specifications were taken from the claimed specifications of the Daimler Gen2 Hydrogen lorry (Fleetowner, 2020), which include two 150 kW fuel cell stacks, two 40 kg hydrogen storage tanks, and a 70 kWh battery pack. Emission intensities for the fuel cell and storage tanks were taken to be 30 kg CO₂e/kW and 500 kg CO₂e/kgH₂ capacity respectively (assuming carbon fibre storage tanks), using the base cases from another Fraunhofer study (Sternberg, Hank, and Hebling, 2019). The embodied carbon of the HFC-EV without the battery pack was therefore estimated to be 79.82 tCO₂e.

Finally, the embodied carbon of an identical typical semitrailer was incorporated for all vehicles, assuming a total mass of 6,810 kg (Firmin, 2016) and a relative proportion of dominant materials from Gaines, Stodoisky and Cuenca (1999). The estimated embodied carbon in a typical trailer is summarised in Table A.4.

Bill of Materials	Estimated Mass [t]	Mass Share [%]	Estimated Emissions [tCO ₂ e]	Emissions Share [%]
Steel	3,318	48.7%	8.10	37.5%
Cast iron	516	7.6%	0.90	4.0%
Aluminium Wrought	2,126	31.2%	11.40	52.5%
Rubber	850	12.5%	1.30	6.0%
TOTAL	6,810 t	100%	22.00 tCO₂e	100%

Table A.4: Estimated embodied carbon for a typical trailer.

The carbon intensity for battery packs was taken to be 100 kg CO₂/kWh in line with the range of current estimates. With this figure, the total embodied carbon of the ICEV, HFC-EV, and a range of BEVs (with battery sizes of 150, 300, 500, 1,200 and 1,500 kWh) is shown in Figure A.7. The hydrogen storage tanks contribute a significant amount of the embodied carbon in the HFC-EV, owing to the large carbon intensity per kg of storage capacity due to the extensive use of carbon-intensive carbon fibre. The battery is the largest contributor from around 500 kWh and up, accounting for around three-quarters of the embodied carbon for the 1,500 kWh scenario. A 1,500 kWh battery pack is would likely be required for a fully battery electric vehicle to achieve similar range to existing diesel ICEVs. A 500 kWh BEV appears to be approximately equal in embodied carbon to the HFC-EV in its assumed specification.

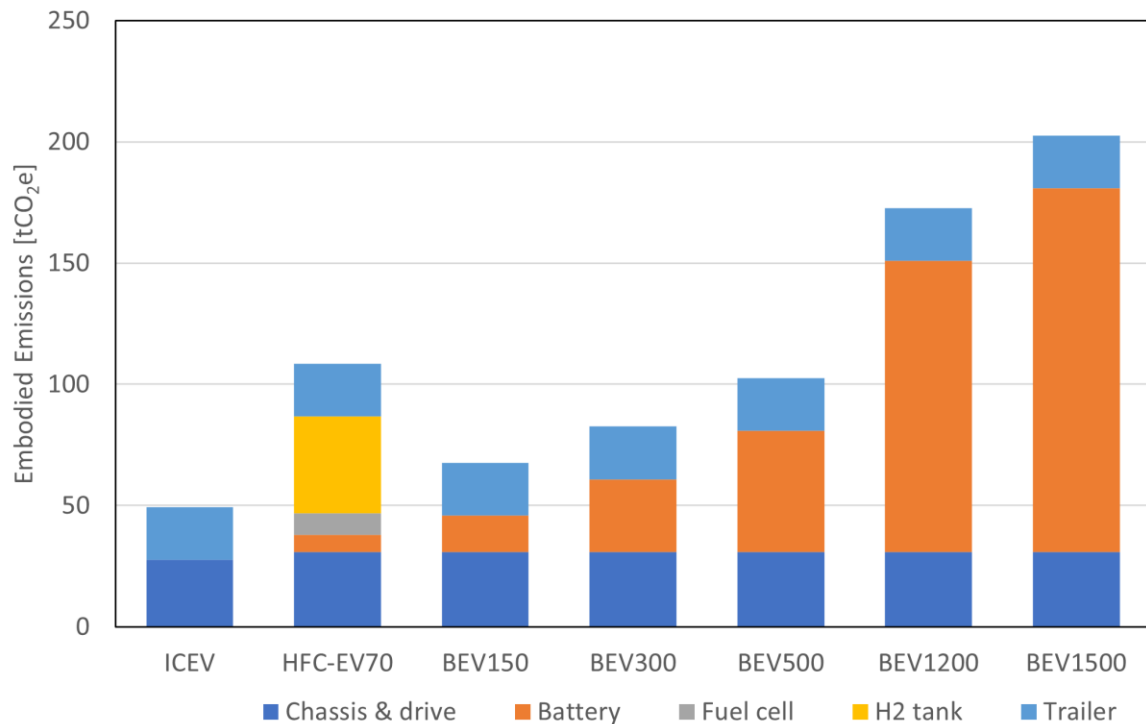


Figure A.7: Estimated embodied carbon for a diesel ICE, HFC-EV, and BEVs with a range of battery sizes (44 t articulated vehicle combinations).

For the detailed economic calculations (Section 7 and Appendix C), the battery size and carbon intensity per kWh have been isolated as variables to enable the sensitivity to these values to be assessed. Case studies on the impact of battery sizing on embodied carbon are given in Appendix G, which demonstrate the impact which ERS has on reducing the necessary battery sizes, and hence the embodied carbon in the vehicles.

b) Infrastructure

Embodied CO₂ emissions associated with the ERS infrastructure were calculated using the best available design specifications and bills of materials available at the time of writing and a few simplifying assumptions. In addition to the embodied emissions in the materials used, some construction activity emissions were also incorporated. The basic ERS design assumed in this study is as shown in Figures A.8 and A.9. A mast spacing of 55 m and substation spacing of 1 km were assumed. In addition, a crash barrier (or ‘passive protection device’) was assumed to be included along the entire length of the ERS, for each lane-km of ERS installation. Specifications of the barrier were taken from JP Concrete (2019) for a barrier unit of length 2.5 m and mass 1,300 kg (giving 525 t per lane-km), as shown in Figure A.10. The relative proportion of steel reinforcing bar by mass in the barrier was assumed to be 3% in line with Hanesch et al. (2022).

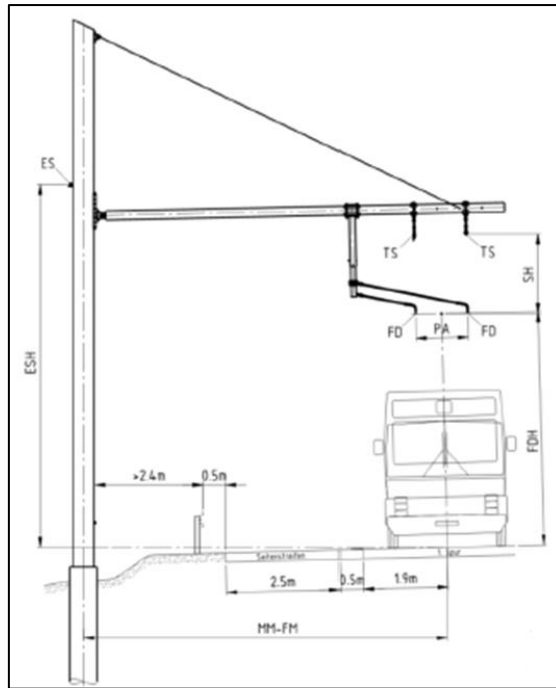


Figure A.8: Schematic of the ERS mast design used to estimate embodied emissions.

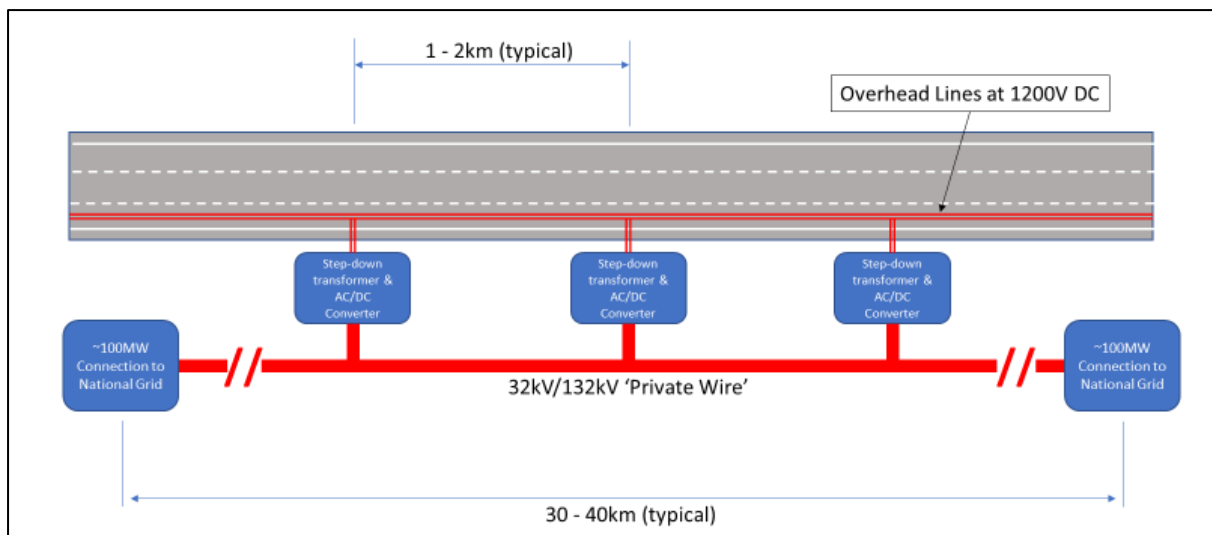


Figure A.9: ERS power supply arrangement assumed to estimate embodied emissions.

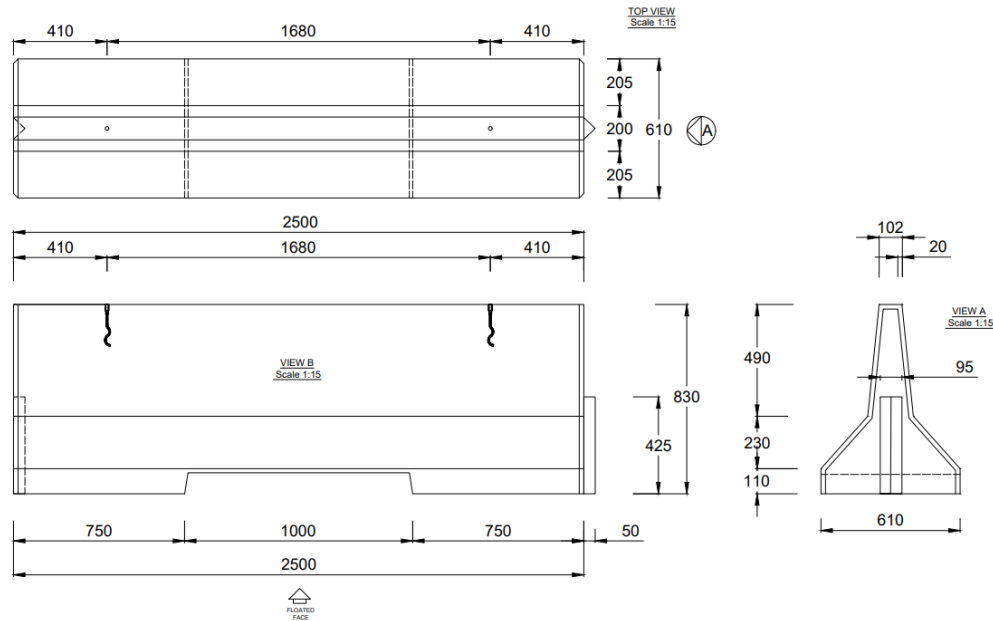


Figure A.10: Roadside passive protection device assumed dimensions (JP Concrete, 2019).

A bill of materials for the masts, overhead lines, and substations were sourced from a recent Fraunhofer study (Wietschel, M. et al, 2017), with some modifications for the mast design which is expected to be different from the original German design. The CO₂ intensities for kilogram of each material were sourced from Granta EduPak ('Ansys Granta EduPack', 2021) using conservative higher estimates were a range of values existed. Summaries of the calculated embodied carbon for the masts, overhead lines, and substations are given in Tables A.5 to A.8.

Component	Material	Embodied Emissions [tCO ₂ e/mast]
Foundation	Concrete	0.09
Foundation	Steel	0.11
Masts	Steel	4.03
Outrigger from the mast	Steel	1.10
Vertical support tube	Steel	0.00
Side holder	Aluminium	0.27
TOTAL		5.60

Table A.5: Estimated embodied CO₂ emissions from the masts.

Component	Material	Embodied Emissions [tCO₂e/lane-km]
Contact Wire	Copper	4.03
Suspension Ropes / Ropes	Bronze	5.06
Cross Links / Hangers	Steel	0.33
<i>TOTAL</i>		<i>9.43</i>

Table A.6: Estimated embodied CO₂ emissions from the overhead lines.

Component	Material	Embodied Emissions [tCO₂e/substation]
Container Structure	Steel	5.33
Container Floor	Plywood	0.21
Container Cladding	Wood	1.78
Container Foundation	Concrete	0.00
Medium Voltage Switchgear	SF6	0.00
	Aluminium	0.62
	Copper	0.96
	Steel	3.38
	Electrical sheet	0.18
	Epoxy resin	2.44
	Plastics	0.07
	Ceramics	0.15
Transformer	Aluminium (0.2%)	0.49
	Steel (24.3%)	10.52
	Copper (21.1%)	14.22
	Electrical steel (25.3%)	10.94
	Insulation material (1.6%)	0.92
Rectifier	Steel (47%)	1.16
	Copper (23%)	0.88
	Aluminium (4%)	0.55
	Polyethylene (1%)	0.02
	Polyamide (2%)	0.16
	Polyester (1%)	0.03
<i>TOTAL</i>		<i>55.03</i>

Table A.7: Estimated embodied CO₂e emissions from the substations

Component	Material	Embodied Emissions [tCO ₂ e/lane-km]
Main Structure	Concrete	64.66
Reinforcement	Steel	36.23
TOTAL		100.89

Table A.8: Estimated embodied CO₂ emissions from the roadside passive protection devices

In addition to the above, the following were also incorporated:

- 'Private wires' were added to account for grid connections, consisting of three copper cables of equivalent size to the contact wires, amounting to 6.04 tCO₂e/lane-km.
- CO₂e emitted from disturbed topsoil was assumed to occur at 34.55 kgCO₂e/ha based on the results of a study on ploughing emissions (Willems, A. B. et al., 2011) and assuming 0.05 ha of disturbed soil area per lane-kilometre of ERS. This amounts to 3.46 tCO₂e/lane-km.
- Earth moving activity for the construction of the substations and buried cable troughs was calculated assuming 5 m³ per substation, 1 m³ per mast, and 1,000 m³ per lane-km for buried cabling. An articulated hauler, excavator and wheel loader was assumed to be operating at an average fuel consumption of 19 litres/hr each (Volvo Construction Equipment North America, no date). This yielded a total figure of 2.1 tCO₂e/lane-km, as shown in Table A.9 below.

	Units per lane-km	m ³ /Unit	m ³ per lane-km
Substations	1	5	5.0
Masts	18.18	1	18.2
Cable Channels (Unit = 1m)	1,000	1	1,000.0
TOTAL			1,023.2

	m ³ /hr	No. Hours	Diesel Use [l/hr]	Embodied Emissions [tCO ₂ e/lane-km]
Excavator (Volvo EC300E)	30	34	19	1.728
Loader (Volvo L180H)	N/A	3	19	0.173
Hauler (Volvo A30G)	N/A	3	19	0.173
TOTAL				2.1

Table A.9: Estimated embodied CO₂e emissions from earthworks (diesel assumed to be 2.68 kgCO₂e/litre).

The total embodied CO₂e of the ERS was calculated to be 255 tCO₂e/lane-km, as summarised in Table A.10.

Component/Activity	Embodied Emissions [tCO₂/lane-km]	Share [%]
Masts	102	40%
Overhead lines	9	4%
Substations	28	11%
Private wires	6	2%
Crash barriers	101	40%
Disturbed soil	7	3%
Construction	2	1%
TOTAL	255	100%

Table A.10: Summary of estimated embodied CO₂e emissions for the ERS infrastructure.

Public static charging sites were assumed to include a single 12 MW transformer connecting to the grid, and 20 x 600 kW static chargers per site. The embodied carbon of the transformers was assumed to scale linearly with power capacity relative to the numbers calculated above, and the embodied carbon of the static chargers was assumed to be approximately equal to an equivalently sized transformer, linearly scaled from the above. It was further assumed that no major earth works would be necessary owing to the use of mostly existing refuelling sites and rest stops. It was hence calculated that each site incorporated 220 t of embodied CO₂e, as summarised in Table A.11 below.

Item	From Fraunhofer	Transformer [tCO₂e]	Chargers [tCO₂e]
Rated MW	6.0	12.00	0.60
Container	7.3	14.66	0.73
MV switchgear	7.8	15.63	0.78
Transformer	37.1	74.19	3.71
Rectifier	2.8	5.59	0.28
Total	55	110	5.5
Number per site		1	20
Total tCO₂e per site			220

Table A.11: Estimated embodied emissions in static charging sites

Note that the above analysis accounts for the initial one-off construction carbon only and is not annualised and excludes yearly maintenance and wear and tear. A more detailed study giving annualised figures was recently published (Hanesch, S. et al., 2022), and the above results compare favourably with these if annualised over 20 years.

A.4 GHG Emissions in Use

'Emissions in Use' represents the tailpipe emissions of the vehicle fleet (vehicles over 25 t). These are generated principally by the combustion process for diesel-powered vehicles and by the emissions at power station sites for electric vehicles. Tables A.12 and A.13 summarise

'snapshot values' for the emissions in use by a diesel 'benchmark' fleet and an electric fleet taking estimated GHG grid intensity values in 2030.

‘Benchmark’ Emissions in Use for Diesel Fleet (Vehicles > 25 t Only)									
Diesel Vehicle	Pop. size	Annual Mileage (km)	Ave. Fuel Cons (mpg)	Fuel Cons. (l/100km)	Average daily range per lorry (km)	Annual Fuel Cons. per lorry (L)	Annual Fleet Fuel Cons. (L)	Fleet Energy Cons. (TWh)	Fleet CO2 Emissions (tonnes CO2)
7.5 – 14 t Rigid	139,732	28,000	11.4	24.8	112.0	6,938	969,459,345	10.24	3,150,743
7.5 – 14 t Arctic	489	66,000	8.9	31.7	264.0	20,948	10,243,381	0.11	33,291
>14 – 17 t Rigid	22,180	28,000	9.1	31.0	112.0	8,692	192,778,558	2.04	626,530
>14 – 17 t Arctic	215	66,000	8.9	31.7	264.0	20,948	4,503,736	0.05	14,637
>17 – 25 t Rigid	57,055	44,000	9.5	29.7	176.0	13,083	746,454,477	7.89	2,425,977
>17 – 25 t Arctic	2,005	66,000	8.9	31.7	264.0	20,948	41,999,958	0.44	136,500
>25 – 33 t Rigid	68,064	43,000	6.7	42.2	172.0	18,129	1,233,933,251	13.04	4,010,283
>25 – 33 t Artic	9,190	66,000	8.9	31.7	264.0	20,948	192,508,534	2.03	625,653
>33 t Rigid	5,387	43,000	6.7	42.2	172.0	18,129	97,661,002	1.03	317,398
>33 t Artic	109,143	93,000	7.9	35.8	372.0	33,253	3,629,378,736	38.34	11,795,481
Lorries > 25 t only	191,784						5,153,481,523	54.44	16,748,815
Grand Totals	413,460						7,118,920,977	75.20	23,136,493

Table A.12: Emissions in Use for Benchmark Diesel Fleet (source: private discussions).

Emissions in Use for Electric Vehicle Fleet (Vehicles > 25 t Only)								
ERS Vehicle	Pop. size	Annual km	Ave Daily Range (250 days p.a.)	Fuel Cons. (kWh/km)	Battery Size (kWh)	Annual Fuel Cons. per Lorry (kWh)	Fleet Fuel Cons. (TWh)	Fleet CO2 Emissions (tonnes – based on Grid CO2 Intensity)
7.5 – 14 t Rigid	139,732	28,000	112	0.9	122.2	24,431	3.41	323,412
7.5 – 14 t Arctic	489	66,000	264	1.5	491.8	98,351	0.05	4,556
>14 – 17 t Rigid	22,180	28,000	112	1.1	153.0	30,606	0.68	64,311
>14 – 17 t Arctic	215	66,000	264	1.5	491.8	98,351	0.02	2,003
>17 – 25 t Rigid	57,055	44,000	176	1.2	268.7	53,748	3.07	290,520
>17 – 25 t Arctic	2,005	66,000	264	1.5	491.8	98,351	0.20	18,682
>25 – 33 t Rigid	68,064	43,000	172	1.7	372.4	74,478	5.07	480,247
>25 – 33 t Artic	9,190	66,000	264	1.5	491.8	98,351	0.90	85,628
>33 t Rigid	5,387	43,000	172	1.7	372.4	74,478	0.40	38,010
>33 t Artic	109,143	93,000	372	1.9	878.2	175,645	19.17	1,816,141
Lorries > 25 t only	191,784						25.54	2,420,025
Grand Totals	413,460						32.97	3,123,509

Table A.13: Emissions in Use for Electric Vehicle Fleet at 2030 Grid Intensity Values (Estimated).

Total figures for GHG emissions in use over the period 2025 – 2050 have been calculated assuming the market penetration rate for electric vehicles shown in Figure A.4. At each year, it is assumed that the vehicle parc remains constant (200,000 vehicles) and that it comprises the appropriate fraction of electric vehicles plus a balance of diesel vehicles. The total GHG emissions in use at each year are calculated as the combination of GHG emissions from the new electric vehicles (making allowance for the declining GHG intensity of grid electricity each year) and the GHG emissions from the balance of diesel vehicles.

A comparison of the aggregated figures for emissions in use and embodied emissions over the entire period are summarised in Table A.14 below.

	Emissions in Use [tCO₂e]	Embedded Emissions in Vehicle and Charging Infrastructure [tCO₂e]	
		Vehicle Base (500 kWh Battery)	Charging Infrastructure
Diesel ‘Benchmark’ Fleet	405,991,274	-	-
Electric Vehicle Fleet	182,096,439	26,337,681	-
ERS Light (5,500 STK)	-	-	1,402,500
Static Charging Network (2,100 Sites)	-	-	241,500
Net Saving/(Expenditure)	223,894,835	(26,337,681)	(1,644,000t)
Net Benefit/(Disbenefit) over 25 years	~195,913,154 tCO₂e		

Table A.14: Summary of the cumulative in use and embodied emissions for the preferred ERS configuration (5,500 STK) from 2025 to 2050.

Appendix B – Journey Simulations

This appendix provides further detail on the calculations presented in Section 3.

B.1 Battery Size Calculation

- Data used for calculations:
 - One week's worth of a supermarket multi-drop operation.
 - Contains 1,226 routes comprising 3,798 vehicle movements, 248,057 vehicle-km (average 65km per movement).
- Distances and expected times for each leg calculated using the GraphHopper routing engine.
- Simple baseline test for overall route length.
- Assumption that average battery consumption is **2.0 kWh/km** and is only ever used between 20-80% (so raw results of the energy needed for a journey must be divided by 0.6 to get the true required battery size) (see Appendix G for detailed simulations to determine the kWh/km).

B.2 Wayside Charging

- This requires keeping a track of “battery dip” so far in each journey, again accumulated at a rate of 2.0 kWh/km, starting at zero at the start of the trip.
- Can simply use the reported distances of each leg at this stage, rather than requiring more detail about the route.
- At each customer, assuming a 500 kW fast charger and a 20 minute opportunity to take on charge, we reduce the accumulative battery dip by a maximum of 166.6 kWh (or reducing to zero if the battery is not yet this discharged).
- Again need to take raw results and divide by 0.6 to obtain the true battery size.

B.3 Routing Algorithm

- Decide on a battery size and pre-calculate the top-up battery limit cap in kWh.
- Consider a collection of n linked journeys and run the “battery dip” algorithm on the collection, either maintaining charge or “topping up” at each intermediate destination as required. Provide the battery dip algorithm with the top-up cap so it outputs representative results.
- Starting from the end, analyse each unwired section in the journey stack. Skip over any unwired section which is either entirely above, or below, the battery size line.
- Pick the first unwired section that “breaches” the battery size line.
- Analyse the battery levels for this leg to find out the location at which the battery reached a “critical” level (e.g. 50 kWh higher than this point) and perform a search for static chargers within a radius of this location.
- For each charger, run the battery dip algorithm on this leg alone to work out the battery dip that would result from taking the journey as far as ORIG, then diverting to CH instead of DEST.
- Rule out any chargers whose battery dip from ORIG -> CH would exceed the battery size.
- We now add the selected charger to the overall itinerary, and reflect this in the battery dip pattern at the point of charge.
- Now have to re-run the algorithm over all journey legs, taking into account this extra waypoint in the itinerary, to find where the next critical point lies.
- Recursively continue until all incursion points have been eliminated.

Appendix C – Financial Analysis

In this appendix, a techno-economic analysis of alternative HGV technologies is evaluated from the perspective of the vehicle owners and infrastructure provider.

C.1 Input Parameters

The financial analysis is calculated using a discount rate of 3% for government and 6% for private infrastructure operators. The fuel prices, assumed constant throughout, are given in Table C.1. The ERS light configuration is used for analysis with an appropriate static charger network, with the costs given in Table C.2. The penetration of ZEVs into the UK HGV parc is shown in Figure C.1.

Fuel Type	Price
Diesel	0.96 £/litre
Retail Electricity (Commercial Rate)	12 p/kWh
ERS Wire Margin (additional fee on-ERS)	Variable p/kWh
Grey Hydrogen	2.50 £/kg
Blue Hydrogen	3.50 £/kg
Green Hydrogen Wholesale Electricity	5 & 12 p/kWh

Table C.1: The fuel prices in this financial analysis. Note that the price of green hydrogen (£/kg) varies over time.

ERS Network Length (Light)	5,500 STK (lane-km)
ERS Maintenance Cost	1% of Capital Costs
Static Charger Network (Low) Total Capital Cost	£6 Bn
Static Charger Network (High) Total Capital Cost	£2 Bn
Static Charger Maintenance Cost	2% of Capital Costs

Table C.2: Specifications and parameters for the ERS Light and public static charging network.

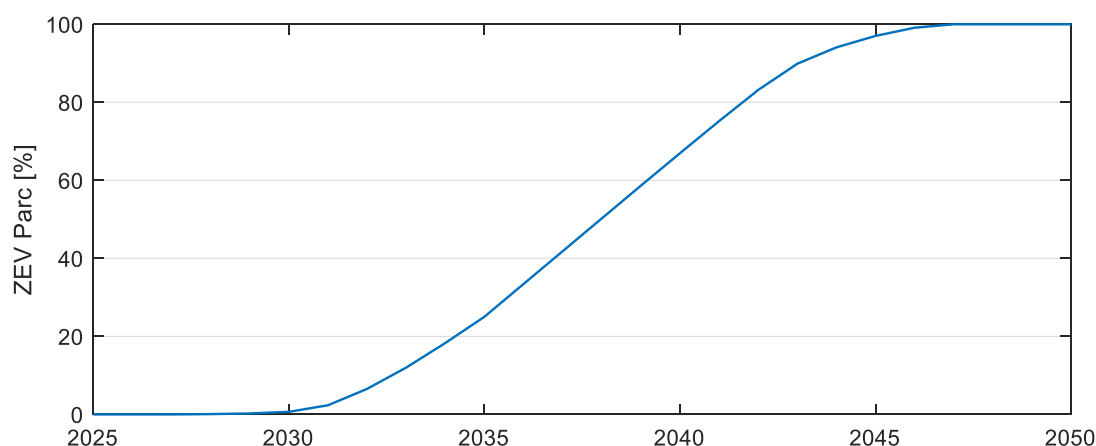


Figure C.1: Assumed uptake of ZEVs across 2025-2050, as a percentage of the total UK HGV parc.

C.2 Infrastructure Provider Perspective

The different ownership models of the infrastructure (ERS and associated public static charging) are examined in this section.

C.2.1 Government Ownership

In this scenario, the government is responsible for building and operating the ERS and a public static charger network to support operators. The TCO of the ‘first-life’ for the vehicles is compared to diesel, and any difference is covered by government subsidy (or tax headroom) through the fuel price. The costs are summarised in Table C.3 and the annual infrastructure capital cost profile is presented in Figure C.2. Figure C.3 shows the NPV from the government perspective for the various hydrogen and BEV/ERS solutions (assuming any difference to baseline diesel TCO is subsidised/claim as revenue through the fuel price).

Note: the BB-EV solution includes a limited public static charger network capped at £2Bn capital cost (see Table C.5 and Figure C.5).

Item	Years	Total Cost
Build Initial ERS (Low Power)	2028-2031	£15.95 Bn (£2.9 Mn/STK)
Upgrade ERS (Full Power)	2035-2045	£6.05 Bn (£0.55 Bn/year)
Build Static Charger Network (High)	2028-2045	£6.00 Bn

Table C.3: Government ownership model costs (see C.2.5 for further details of ERS STK costs).

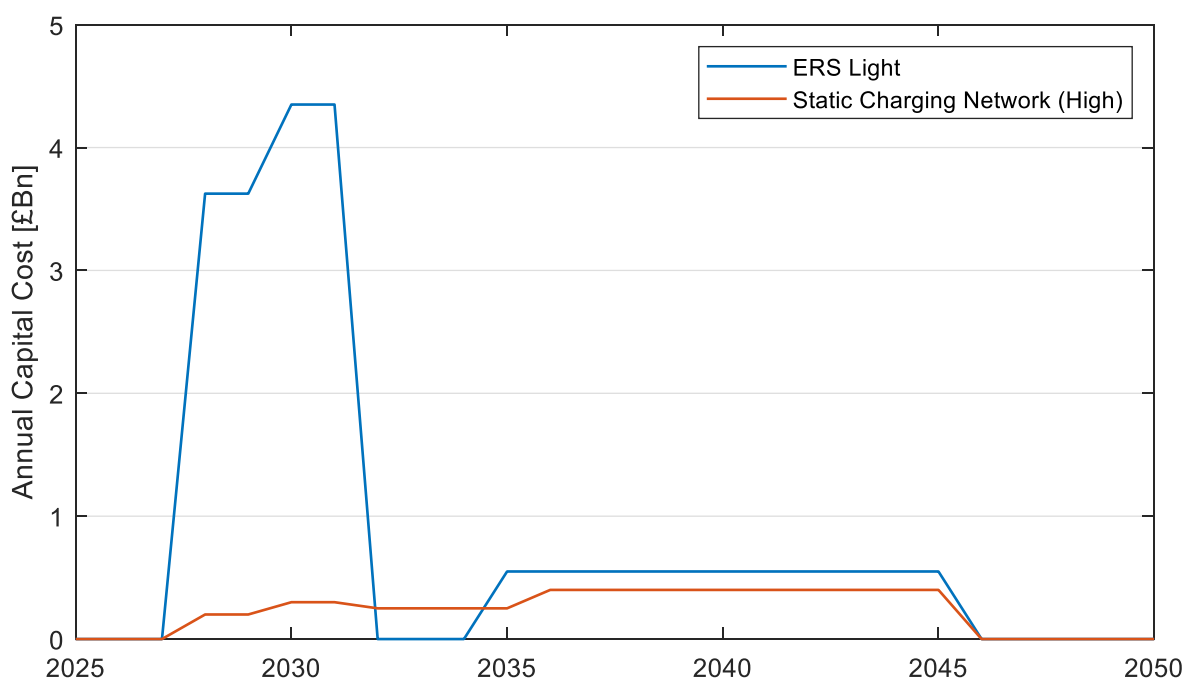


Figure C.2: Annual capital cost for the ERS and static charger network under the government ownership model.

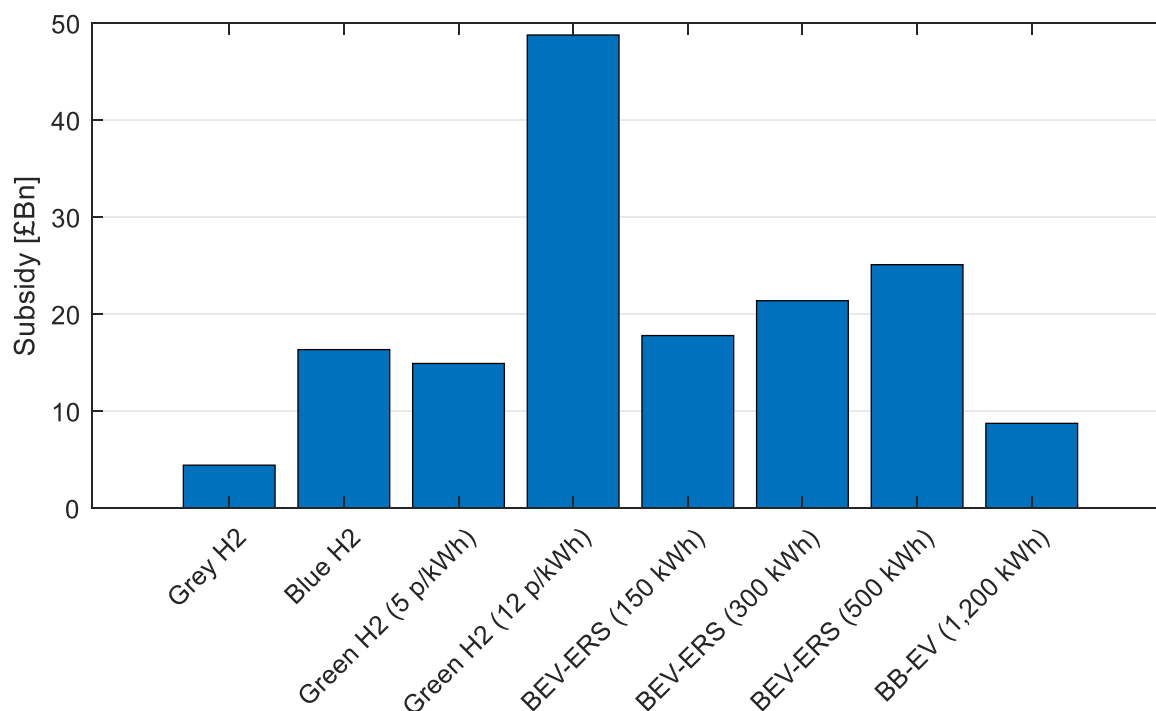


Figure C.3: NPV for the government from 2028-2050 (3% discount rate).

C.2.2 Free Market Ownership

Under this scenario, there is no government intervention, and a private operator constructs and operates the ERS, along with a static charger network (Low). There is no comparison to the TCO of diesel lorries, only directly with BEV-ERS and green hydrogen powered HFC-EVs. The costs are summarised in Table C.4. The annual capital expenditure follows the same profile as the government ownership model. Figure C.4 shows the NPV for the private ERS owner for a combination of ‘wire margins’ and on ERS percentages of journeys.

Item	Years	Total Cost
Build Initial ERS (Low Power)	2028-2031	£15.95 Bn (£2.9 Mn/STK)
Upgrade ERS (Full Power)	2035-2045	£6.05 Bn (£0.55 Bn/year)
Build Static Charger Network (High)	2028-2045	£6 Bn

Table C.4: Free market ownership model costs (see C.2.5 for further details of ERS costs).

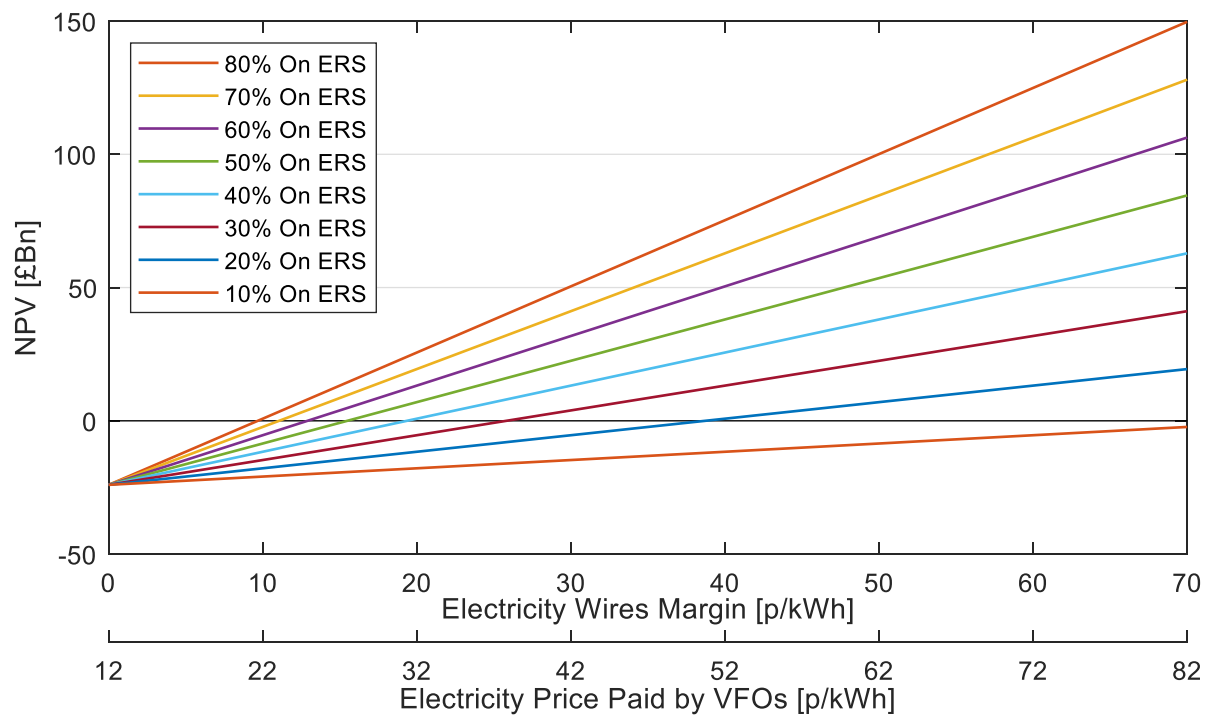


Figure C.4: NPV for the private operator from 2028-2050 for different on ERS percentages.

C.2.3 Hybrid Ownership

The final scenario examines a hybrid ownership model, where the government builds out the initial low power ERS network. The costs are summarised in Table C.5 and shown in Figure C.5.

Item	Who	Years	Total Cost
Build Initial ERS (Low Power)	Government	2028-2031	£15.95 Bn (£2.9 Mn/STK)
Build Static Charger Network (Low)	Government	2028-2037	£2 Bn
Purchase ERS at Auction	Private	2035	£19.28 Bn
Upgrade ERS (Full Power)	Private	2035-2045	£6.05 Bn (£0.55 Bn/year)

Table C.5: Hybrid ownership model costs (where the auction price is the government's capital investment plus 10%) (see C.2.5 for further details of ERS STK costs).

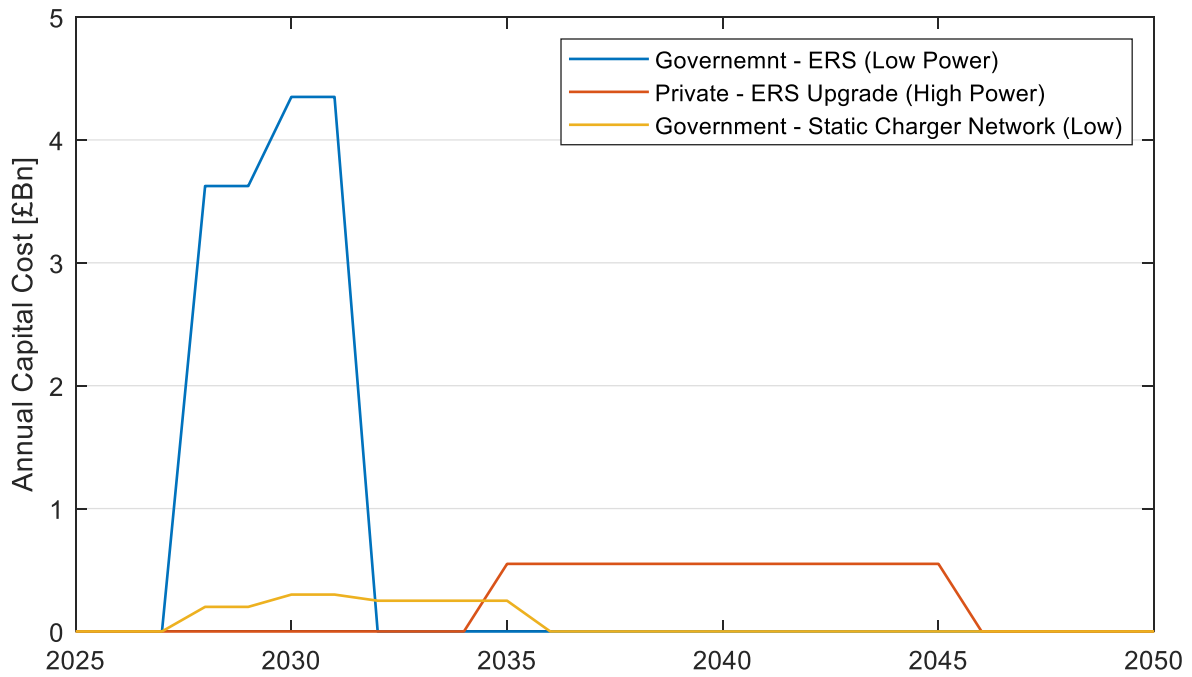


Figure C.5: Annual capital cost for the ERS and static charger network under the hybrid ownership model (excluding auction price).

A series of NPVs have been calculated for the private operator from 2035 to 2050, 2060, and 2070 in Figure C.6, C.7, and C.8, respectively, for different wire margins and on ERS percentages of journeys.

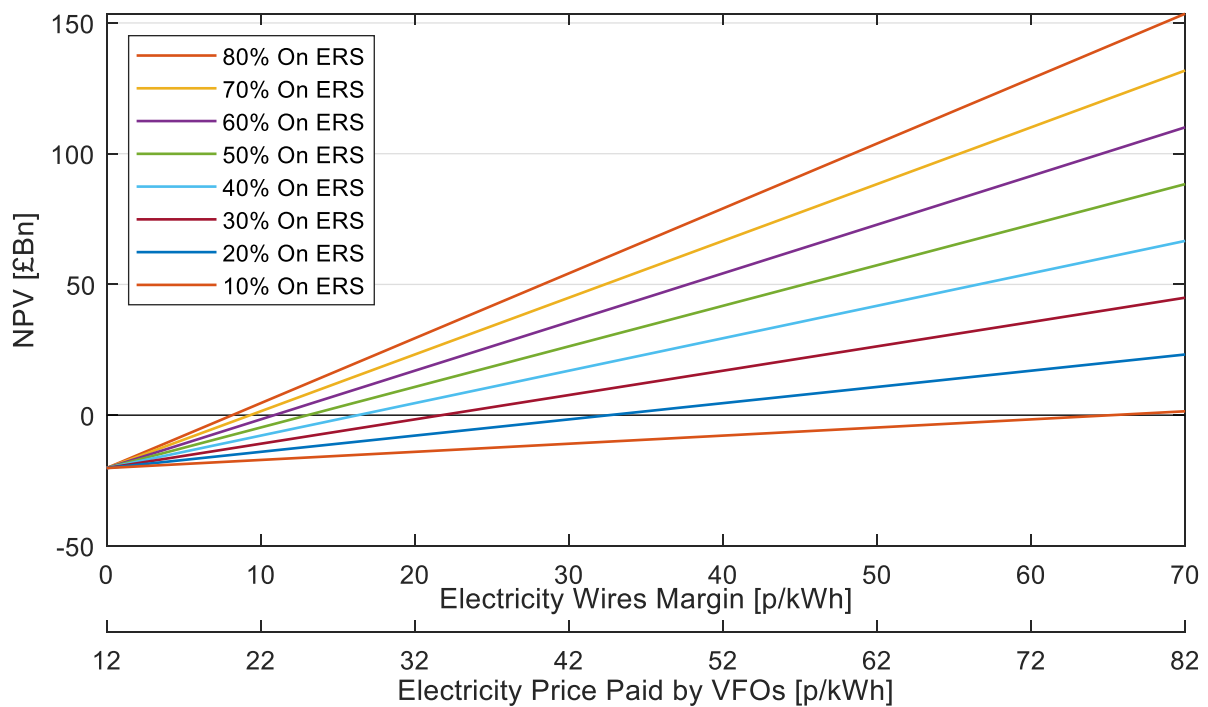


Figure C.6: NPV for the private operator from 2035-2050 (6% discount rate).

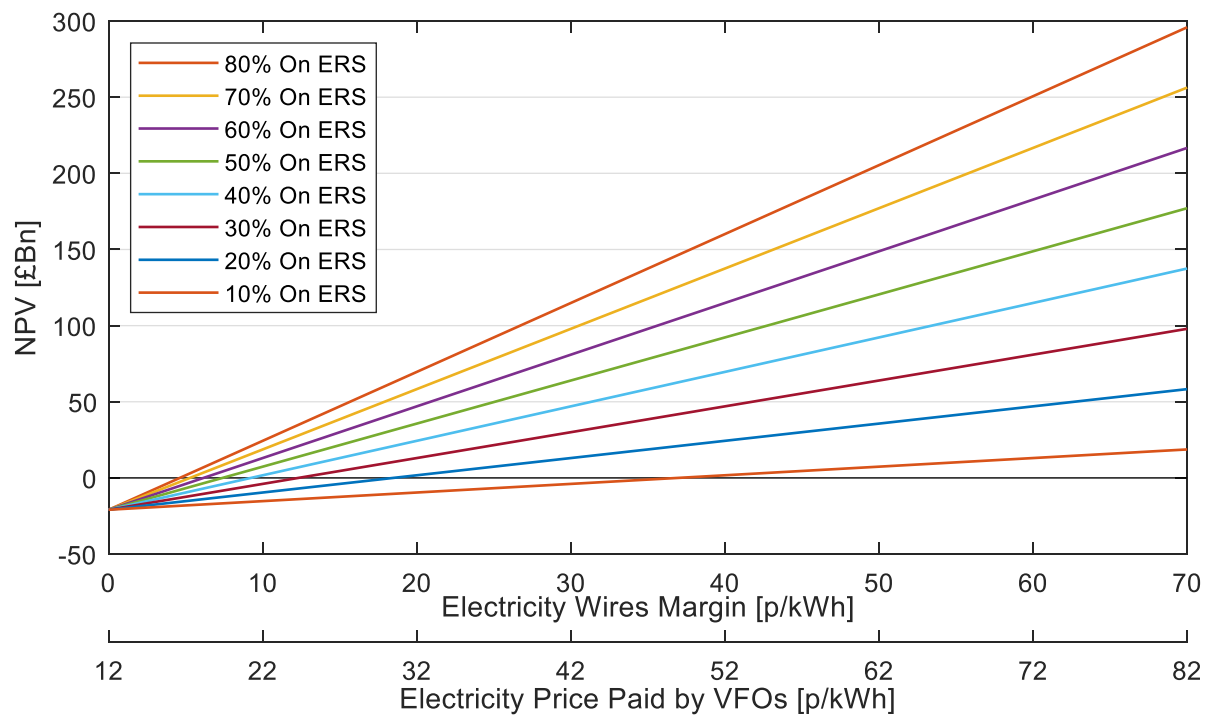


Figure C.7: NPV for the private operator from 2035-2060 (6% discount rate).

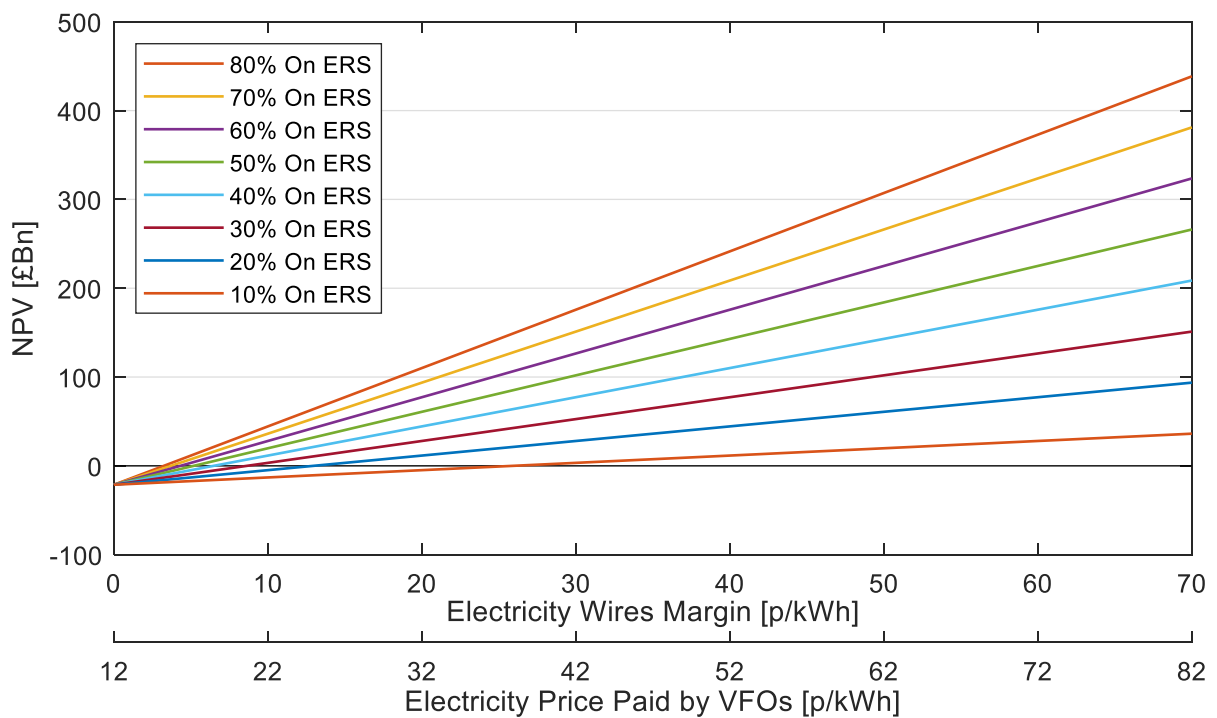


Figure C.8: NPV for the private operator from 2035-2070 (6% discount rate).

C.2.4 Initial and Outer- Bound ERS STK Costs

Category	Item	Cost (2 MW/STK)	Cost (0.5 MW/STK)	Assumptions
Design	Civils Design Power Supply (Included in 'Direct Works' Packages below) OLE (Included in 'Direct Works' Packages below)	£3Mn (£100k/STK)	£3Mn (£100k/STK)	Assumes significant design efficiencies will be achieved by 2028 as a result of increasing automation.
On-Site Preliminaries	Site Office Complex Construction Management Temporary Works Traffic Management	£21Mn (£700k/STK)	£21Mn (£700k/STK)	Assumes significant process & organisational improvements will be achieved with DfT committing to a long-term 'Programme Approach' to procurement. Assumes a construction approach can be developed to enable a 'no contraflow' working arrangement during build-out.
Direct Works: Civils	Permanent Crash Protection Plinths for Sub-Stations Bridge Modifications Drainage, Earthworks and Landscaping Electrical, Communication, Lighting, & Signage Miscellaneous	£19Mn (£633k/STK)	£19Mn (£633k/STK)	Assumes normal rates of continuous improvement.
Direct Works: Traction Power Systems and Overhead Line Equipment	Grid Connections	£12Mn (£400k/STK)	£3Mn (£100k/STK)	Assumes major improvements in grid connection costs as a result of a long-term plan, greater transparency, and possible change in policy.
	Traction Power Sub-Stations	£32Mn (£1.1Mn/STK)	£8Mn (£270k/STK)	Assumes major improvements in TPS unit costs due to long-term purchasing commitments and the economies of volume manufacturing.
	Masts and Catenary Systems	£18Mn (£600k/STK)	£18Mn (£600k/STK)	Assumes normal rates of continuous improvement.
Other Costs	Land Costs, Statutory Undertakers NR VAT Lead Contractor Fee	£15Mn (£500k/STK)	£15Mn (£500k/STK)	Assumes significant improvements as a result of adopting a long-term programme approach.
TOTAL (£M)		£120Mn	£87Mn	
COST/STK		£4Mn/STK	£2.9Mn/STK	

Table C.6: Estimated ERS Construction Costs at 2028 (constant 2022 value of money).

Appendix D – The Price of Hydrogen

In this appendix, the cost of hydrogen generated by a number of different processes (SMR, alkaline electrolysis, and PEM electrolysis) is calculated. We also look at different means of generating and distributing the product, including central generation and distribution and local generation. In each case, the final step of the calculation is to estimate the price of hydrogen per kg ‘at the nozzle’. These calculations are carried out at a variety of different points along the 2021 – 2050 timeline.

It is recognised that some hydrogen technologies (e.g. SMR) are mature, whilst others are still evolving (e.g. PEM electrolysis). In the following calculations, the price of mature technologies is assumed to remain constant with time, whilst the price and efficiency of evolving technologies is assumed to improve with the passing of time according to rules which are defined in the text. The following figures and tables summarise the costs of hydrogen storage tanks, alkaline electrolyzers and associated grid connections, and the wholesale cost of the hydrogen itself.

Tank Capacity [kg]	30	100	500	1,000	3,000	12,000
2021 Price [£/kg]	1,200	1,000	800	700	600	500
Mature Target Price [£/kg]	500	500	450	400	350	300

Table D.1: Cost of hydrogen storage tanks.

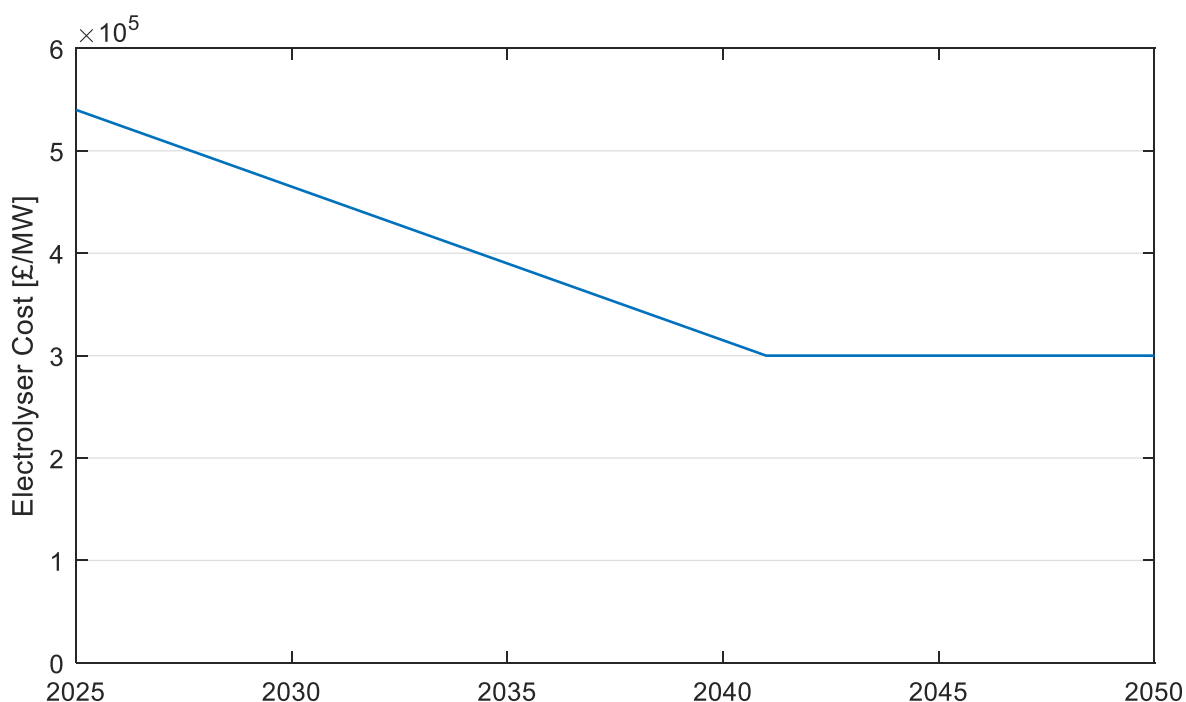


Figure D.1: Cost reduction profile of alkaline electrolyzers at 30 MW scale.

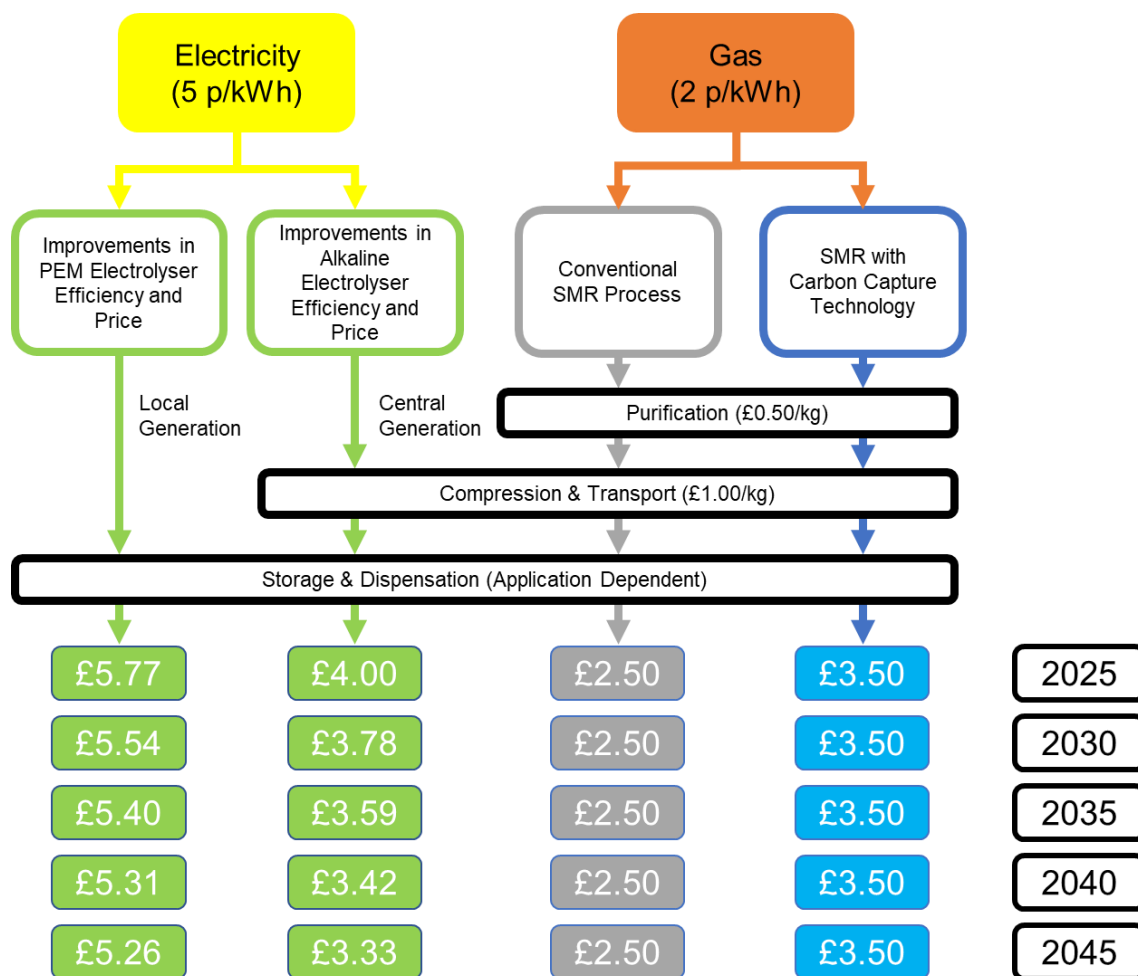


Figure D.2: Price of Hydrogen (wholesale electricity price of 5 p/kWh).

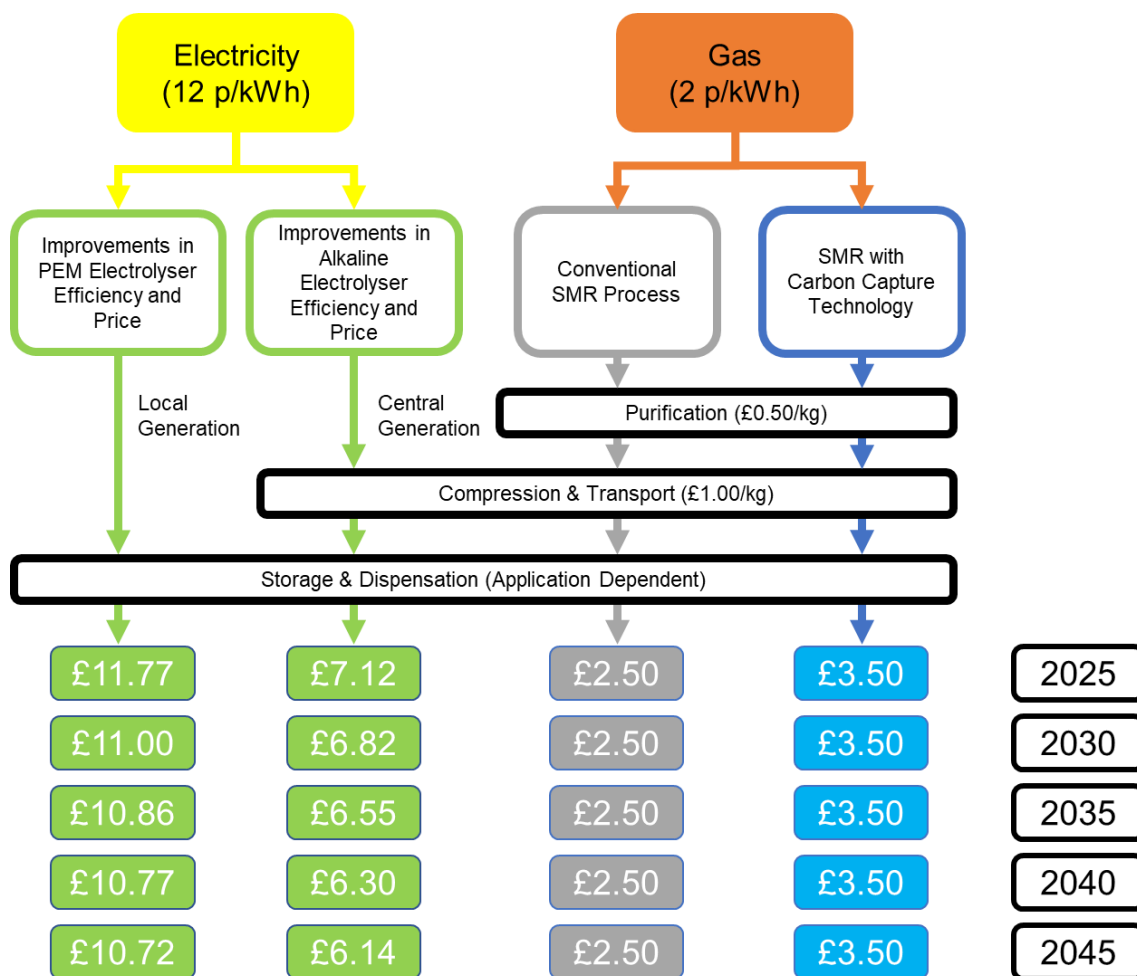


Figure D.3: Price of Hydrogen (wholesale electricity price of 12 p/kWh).

Appendix E – Low Bridges

E.1 Introduction

This appendix summarises current thinking in WP4 regarding the issue of ‘Low Bridges’. This is considered to be a critical issue because there are between 1,000 and 2,500 road features¹ on the Strategic Road Network (SRN) which meet this description, depending on the strict definition of the term (see ‘Low Bridge Definition’ below). Worse, some of these bridges are ‘clustered’ in concentrated zones along the motorway network, leading to long stretches which will be difficult to electrify due to the frequency of the bridges.

¹ *Note that here a ‘road feature’ does not necessarily represent an individual bridge or gantry, but rather an individual height measurement which can be unique for each lane. For example, a single bridge which spans a dual carriageway with four lanes in each direction would be represented 10 road features, one for each lane including the hard shoulder in either side direction, each with their own height measurement data point.*

E.2 Low Bridge Definition

A ‘Low Bridge’ is defined as one which is unable to accommodate the Siemens’ OLE without the contact wire running at a height less than 5.0 m. This height is defined by the need to allow trailers with a maximum height of 4.95 m to pass freely under the bridge whilst maintaining an electrical clearance of 50 mm between the wire and the top of the vehicle.

NOTE: A 50mm electrical clearance reflects the transient clearance requirements of EN50119. However, it violates the clearance of 460 mm required by the Light Rail Safety and Standards Board (See the appendix to this note). Some might argue that the LRSSB approach should set the design standard.

At the time of writing, the minimum clearance which can be engineered by Siemens between the contact wire and the bridge soffit is around 200 mm. This leads to the definition of a ‘Low Bridge’ being set at 5.2 m (or 5.66 m if the LRSSB requirements are to be met). The distribution of road features along the SRN is shown in the figure below. There are around 2,500 structures which are less than 5.2 m and around 9000 which are less than 5.66 m.

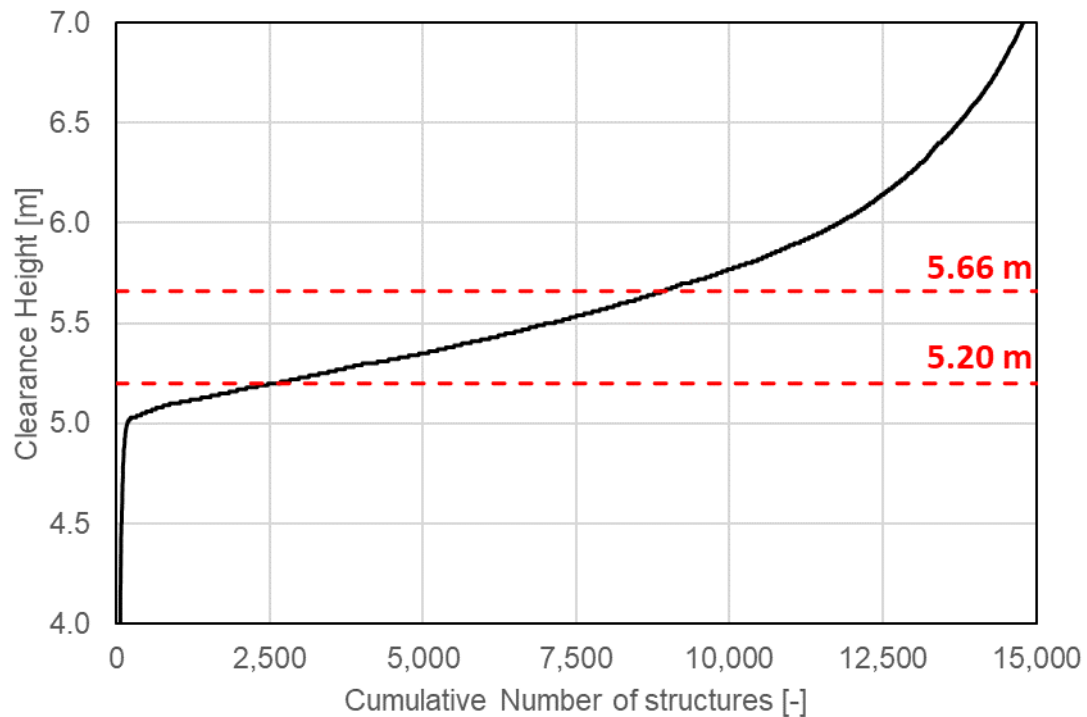


Figure E.1: Distribution of road feature clearance heights on the strategic road network.

E.3 Case Study – M1/M6 Corridor

A brief case study has been conducted for the M1/M6 corridor between Watford (London) and Carlisle. This corridor has been chosen because it is one of the most heavily trafficked stretches of motorway in the UK with a very heavy intensity of warehousing along the route. It represents a 'must do' section for any national ERS system. The definition of a 'Low Bridge' has been taken as 5.2 m for this case study. The conclusions would be considerably worse if a criterion of 5.66 m had been adopted. The distribution of Low Bridges along the M1/M6 corridor is shown in the figure below.

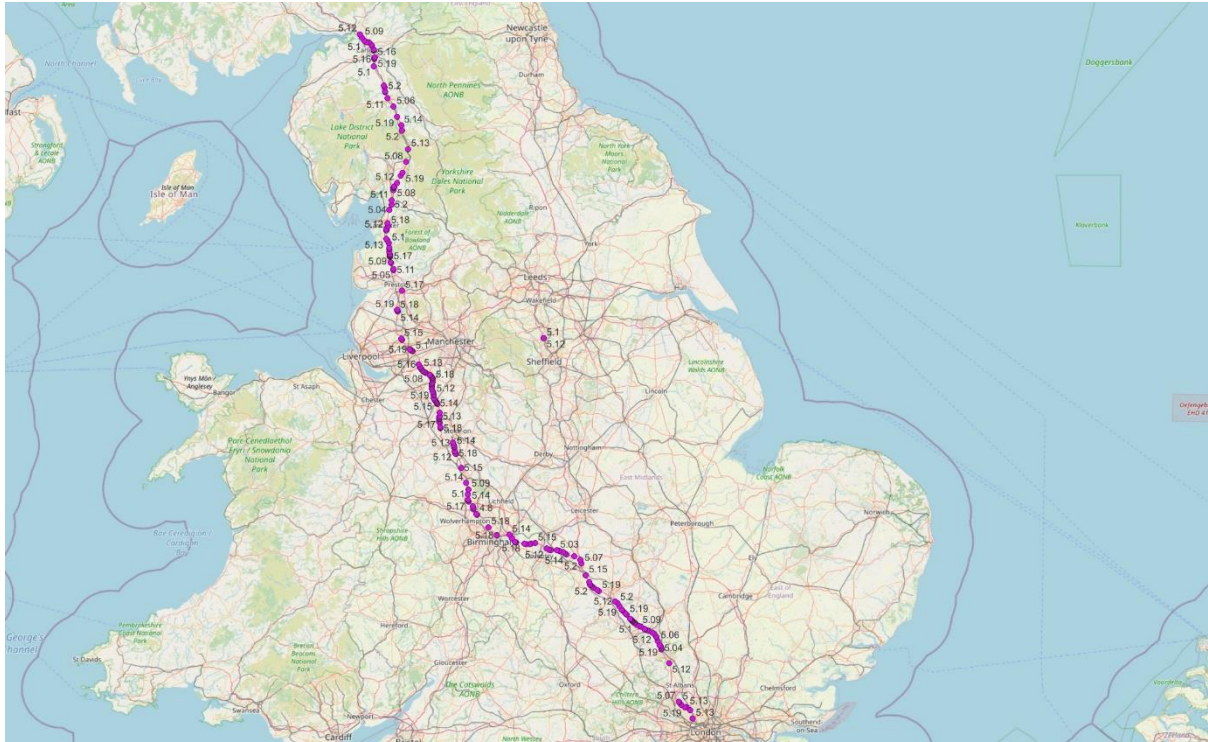


Figure E.2: Bridges <5.2 m on the M1/M6 corridor.

Over the entire corridor length, there are 199 “structures” (i.e. an entire bridge or gantry) with at least one feature clearance of less than 5.2 m, as summarised in Table E.1. Note that in this table the term “structure” is used to refer to a single structure site, i.e., a single bridge or single gantry, unlike the ‘road feature’ which refers to each measurement per lane. The frequency of bridge occurrence varies along the length of the corridor and two particular sections have been studied in more detail. These are the stretches between Luton – Northampton just north of London, and Sandbach – Warrington in the area around Manchester. It can be seen from the table and diagrams below that bridges occur very frequently in these two zones. This suggests that the contact wires might need to be discontinued for unacceptably long distances if the current Siemens’ approach is not adapted.

	No. < 5.2m structures	Distance (miles)	Structures per mile	Miles per structure
Total M1/M6 London to Carlisle	199	308.8	0.64	1.6
Luton to Northampton	31	34.2	0.91	1.1
Sandbeach and Warrington	32	22.4	1.43	0.7

Table E.1: Bridge data for M1/M6 corridor.

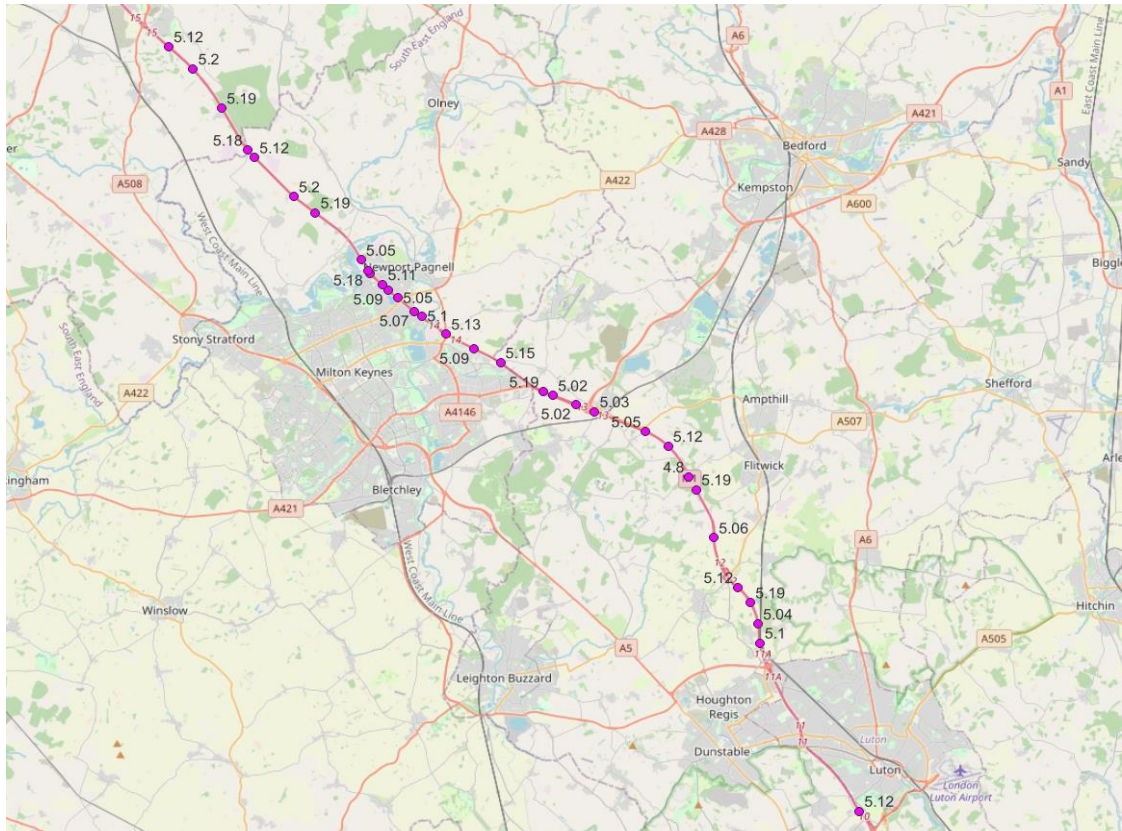


Figure E.3: Bridges <5.2 m on the Luton – Northampton stretch of the M1.

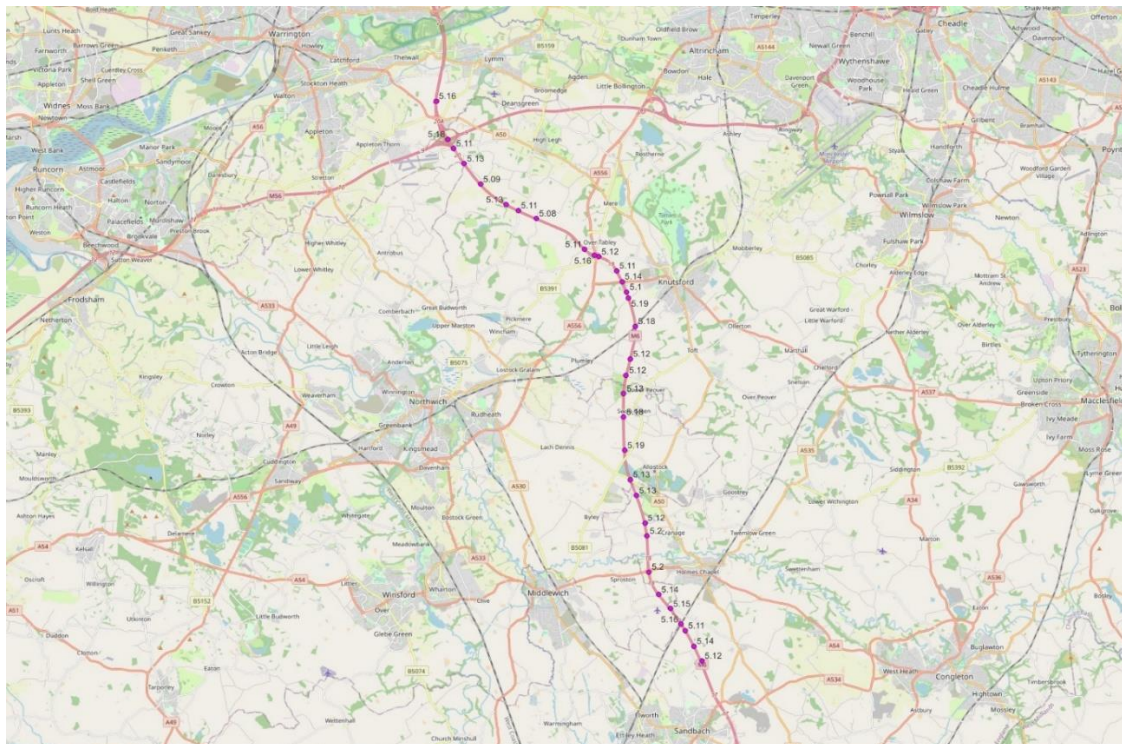


Figure E.4: Bridges <5.2 m on the Sandbach – Warrington stretch of the M6.

E.4 Conclusions

It is not unusual for Low Bridges (<5.2 m) to occur at intervals in the order of 1-1.5 km over stretches of motorway in the range 30-50 km. It would be unacceptable to discontinue the OLE over such long stretches in critical areas of the motorway network and this suggests ERS solution, as currently proposed by Siemens, is not optimal for some areas in the UK.

A solution needs to be found which reduces the clearance required between the bridge soffit and the contact wire (currently around 200 mm). A clearance of 30 mm would reduce the 'Low Bridge' definition to 5.03m and this would accommodate almost all the bridges on the SRN. A design concept has been suggested which we consider to be technically feasible and capable of coming close to this objective. The scheme is shown in outline in the diagrams below. Something of this nature will need to be developed and demonstrated if the ERS solution is to be considered workable for the UK.

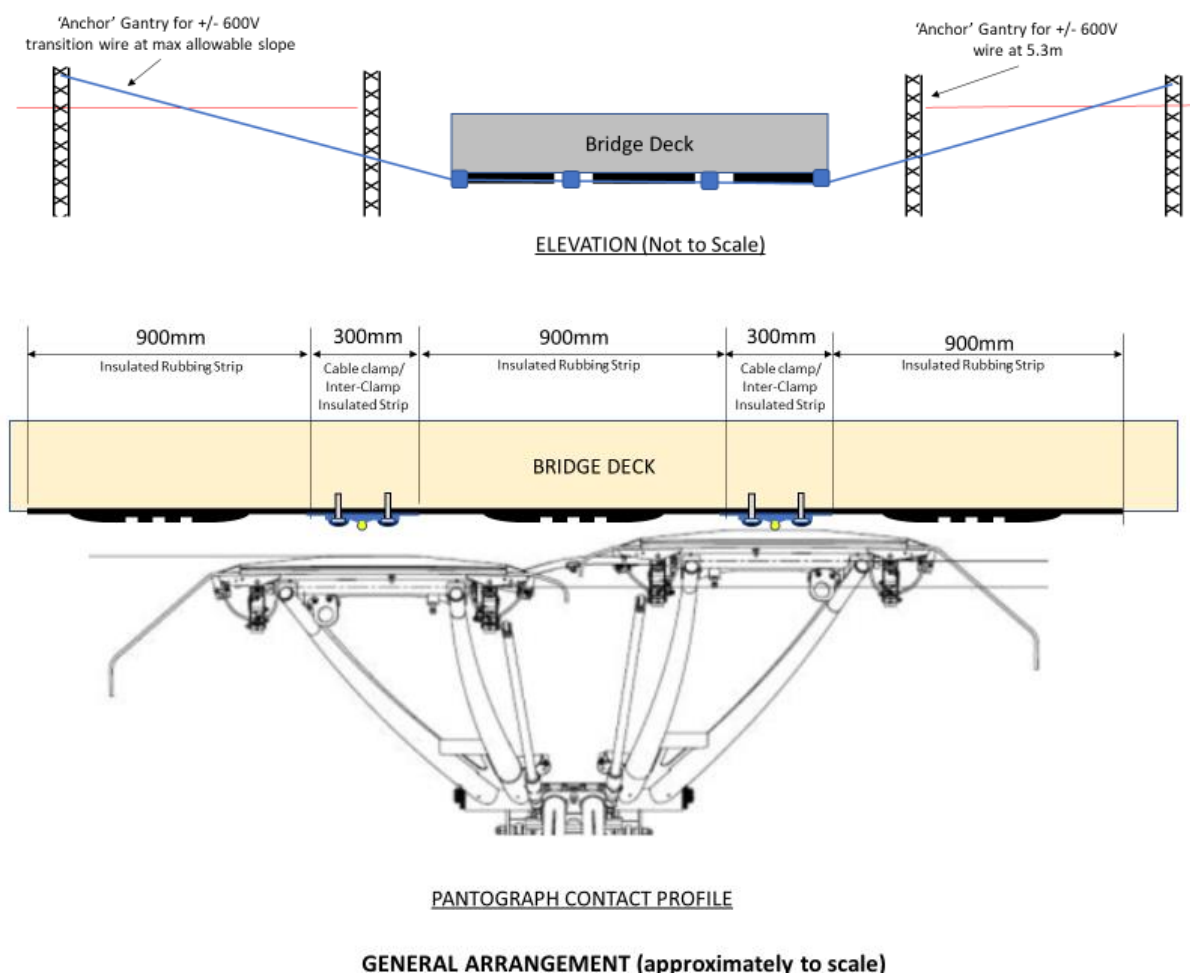


Figure E.5: Proposed schematic of potential low bridge solution of the (top) bridge deck and OLE, and (bottom) pantograph-bridge deck interaction.

Appendix F – Static Charger Sites

F.1 Unit Costs

The following unit costs have been used to calculate the cost of building static charging sites. Prices have been identified at 2020 prices for 50 kW and 150 kW chargers and it has been assumed that these prices will remain relatively stable in future reflecting the relative maturity of the products. 600 kW DC chargers with cable-connect facilities are not yet commonly available (although pantograph DC chargers at these power ratings are available). For these products, prices have been estimated for 2028 (the proposed start of system build-out).

a. Unit Costs

Unit Power [kW DC]	50	150	600
Installed Cost [£]	£20,000	£50,000	£150,000

Table F.1: Charger unit power ratings and installed costs.

b. Site Connection Costs

The cost of making a connection to the local electricity distribution network is conventionally estimated by the District Network Operator (DNO). This is an opaque process and widely different costs are often reported for similar installations made by different DNO's at different locations. This puts some uncertainty into the process for estimating future connection costs for charger sites.

Broadly, there are two types of site connection which might be made.

- A site which is chosen because of its proximity to a convenient point of connection to the local grid.
- A site where the location is fixed by other considerations (e.g. a transport depot) and which may, as a result, be located quite inconveniently when it comes to making a connection to the grid.

An indication of the potential difference in connection costs is presented in Tables F2 and F3 below.

Connection Rating [MW]	0.05	0.15	0.30	0.50	1.00	2.00	3.00	5.00	8.00	12.00
Price [£k]	30	50	150	300	500	1,000	2,000	3,000	3,500	4,000

Table F.2: Grid connection costs for private depots (source: Professional Advice).

Connection Rating [MW]	0.10	1.00	3.00	5.00	8.00	12.00	15.00
Price [£k]	100	180	340	500	740	1,000	2,000

Table F.3: Grid connection costs for public infrastructure (source: BOX).

It is assumed that charger sites will be chosen based on their proximity to convenient points of connection to the electricity grid. For this reason, the grid connection costs shown in Table F4 below have been taken from the lower of the two ranges in Table F2.

Connection Rating [MW]	1	4	7
DNO Connection Cost (assuming connection to HV Network) [£]	£200,000	£450,000	£650,000

Table F.4: Site connection power rating and cost.

F.2 Site Costs

a. Small Sites

3 x 600 kW chargers	£450,000
1 x 2 MW grid connection	£250,000
Site construction work	£300,000
TOTAL	£1,000,000

b. Large Sites

12 x 600 kW chargers	£1,800,000
1 x 7 MW grid connection	£650,000
Site construction work	£950,000
TOTAL	£3,400,000

Appendix G – Vehicle Energy Consumption Analysis

G.1 Simulation model

The simulation model is summarised in Figure G.1 and comprises two sub-models: the drive cycle generator and the detailed vehicle model. The drive cycle generator is implemented in Python and takes as inputs an origin and destination pair (in GPS coordinates) which defines a given journey, as well as the locations of any drop-off stops along the route. The drive cycle generator is also provided with the possible ERS topographies in the form of GIS polygons, and the available static charging capacity in kilowatts at each stop (which can be zero). Utilising the HERE Maps routing API, the programme generates a GPS-defined route (using the fastest time condition), a target speed profile based on posted speed limits and assumed acceleration and deceleration rates, an elevation profile, and two charging profiles (binary signals indicating the existence of ERS or static charger sections along the route.) Stop-start manoeuvres were included at any intersections and roundabouts. An overriding speed limit of 90 km/h was enforced. Traffic effects were neglected.

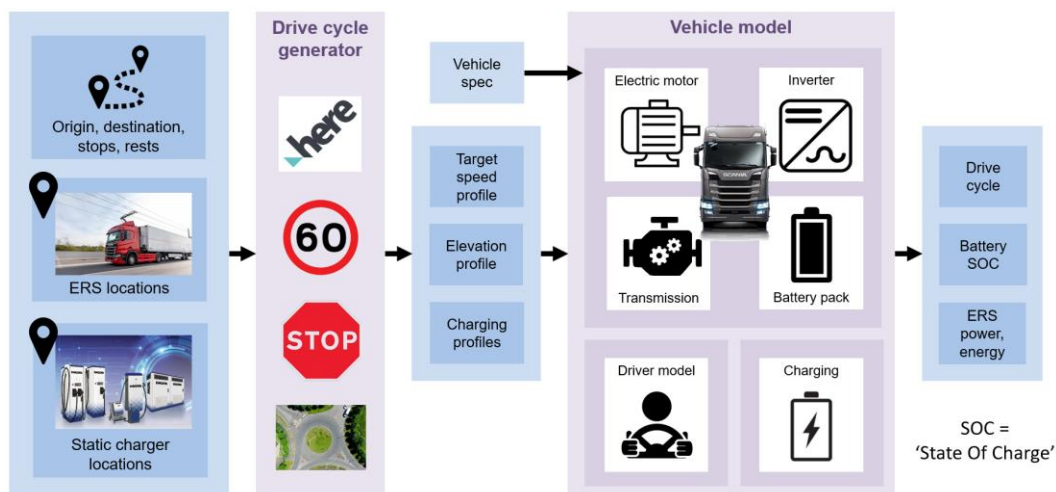


Figure G.1: Simulation model, comprising the drive cycle generator (left) and vehicle model (right)

The detailed vehicle model was implemented in MATLAB/Simulink, building on an existing validated battery electric vehicle model (Madhusudhanan et al., 2020). The model includes an inverter, electric machine, transmission, driver model, vehicle dynamics model, regenerative braking, and a battery module which includes ERS and static charging functionality. The model takes the drive cycle as an input, along with a set of vehicle specifications, and outputs a fully characterised time history of vehicle performance along the simulated journey, including power, energy consumption, speed and acceleration profiles, and battery state-of-charge. The model also outputs the power demanded and energy consumed from the ERS.

Additional information on the vehicle model is given in Figure G.2. The ERS charging functionality and associated logic was introduced in consultation with ERS experts at Scania and Siemens. It was assumed that when on the ERS, the ERS supplies the vehicle the full power demanded by the inverter, and simultaneously charges the battery at an assumed rate of 150 kW. Regenerative braking operates as usual, and a negative inverter power is used to charge the battery and is not fed back into the ERS. For now, no limit has been imposed on the amount of power which can be drawn from the ERS, but in the simulations this rarely

exceeds 300 kW. A vehicle mass of 44 t, the heaviest permissible by regulation, was assumed throughout the journey. Auxiliary loads were added for trailer refrigeration and cabin heating, assuming an efficient heat pump heating system, and typical refrigeration cycle loads as published by Zemo (Robinson, and Fraser, 2021). A summary of important parameters is given in Table G.1 (some cannot be shared due to the sensitivity of data provided by Scania and/or Siemens).

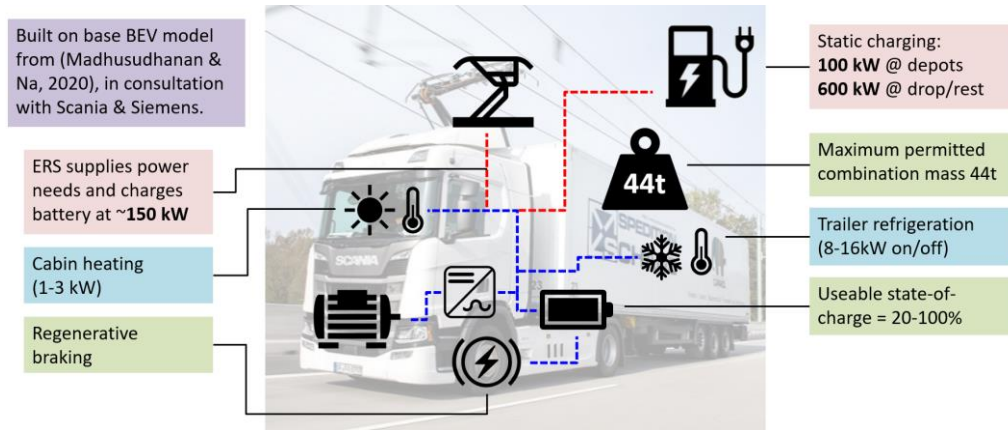


Figure G.2: Additional information regarding the vehicle model

Parameter	Description	Value
m	Vehicle mass	44,000 kg
C_{rr}	Rolling resistance coefficient	0.006
C_D	Aerodynamic drag coefficient	0.7
A	Frontal area	7 m ²
d	Rolling diameter of driven wheel	1.0125 m
ρ	Density of air	1.225 kg/m ³
P_{refrig}	Trailer refrigeration power (average continuous)	4 kW
P_{heat}	Cabin heating power (average continuous)	1 kW
η_{drive}	Overall driveline efficiency	92%
V_{max}	Maximum vehicle speed	90 km/h
SOC_{usable}	Usable battery state of charge	80%
SOC_{range}	Range of usable battery state of charge	20-100%
$P_{ERS,battery}$	ERS battery charging power capacity	150 kW
P_{depot}	Depot charger power capacity	100 kW
$P_{rest\ stop}$	Rest stop charger power capacity	600 kW
$P_{drop-off}$	Drop-off (warehouse/retailer) charger power capacity	600 kW

Table G.1: Summary of primary simulation parameters.

The final output from the vehicle model includes a fully characterised drive cycle time-history, an example of which is given in Figure G.3. The top plot shows the vehicle target speed in the dashed black line (as output by the drive cycle simulator), the actual speed as achieved by the vehicle/driver model in the solid black line, and the elevation profile in red. Sections of the journey on an ERS section of road are shaded grey. Extended periods of zero speed indicate stops. Five 20-minute drop-off stops are evident in the example shown, as well as a longer 45-minute rest stop at around 5h30m. The bottom plot shows the resultant battery state of charge profile in black, as measured in 'battery dip' (total energy consumed). Also shown are any charging opportunities via ERS (blue) or static charging (red). The availability of the charging is shown as a dashed line; the line is solid where the battery actually draws charge from this (usually up to the point of 100% SOC, after which no additional power is drawn).

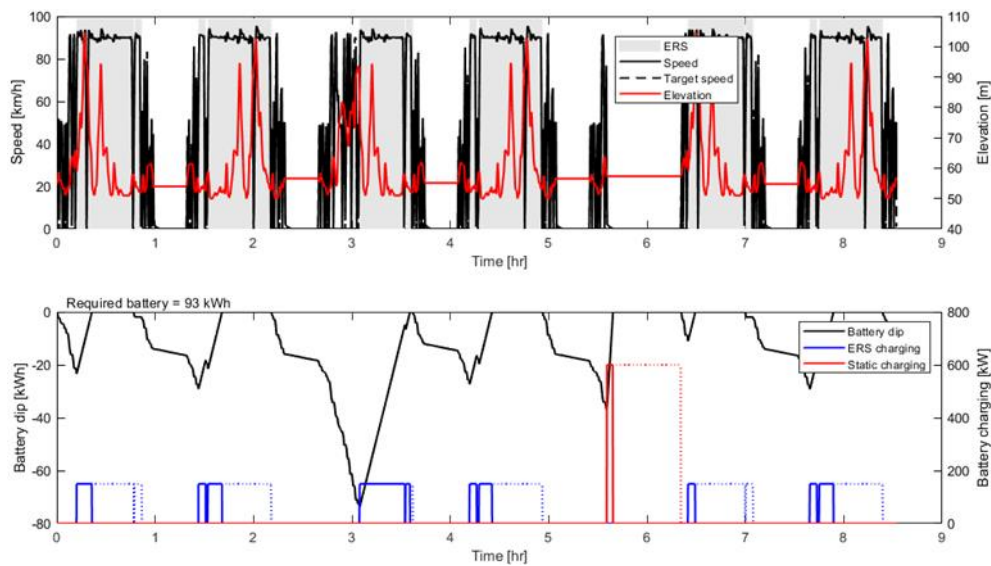


Figure G.3: Sample drive cycle and battery state of charge output from the simulation model

Using battery dip instead of battery SOC allows us to identify the minimum battery size which *would have* been required for the journey without assuming a given battery size at the beginning of the journey. This does, however, assume a full SOC at the start of the journey. The required battery size is found from the minimum battery dip over the journey and the assumed usable state of charge range (20-100% SOC gives an 80% SOC range). The required battery capacity for the example shown is 94 kWh – a relatively small battery given the extensive availability of ERS along the route. This is calculated as follows:

$$\text{battery capacity required} = \frac{-\min(\text{battery dip})}{\text{SOC}_{\text{usable}}}$$

The original underlying electric vehicle model upon which the 44 t lorry model was built was developed for an electric bus and was validated against in-service drive cycle data from a 'Metrocity' electric bus manufactured by Optare Group Ltd. and operated by Stagecoach in London (Madhusudhanan et al., 2021). Figure G.4 demonstrates the results of the validation, showing good agreement of the battery state of charge (SOC) as well as the overall energy consumption. Given the previous validation of the electric bus model, and the corroboration of any model and parameter updates with Scania and Siemens, the ERS model is deemed to be acceptably accurate for the current simulations. Future validation and optimisation work may be carried out once the ERS vehicle and infrastructure are available for testing.

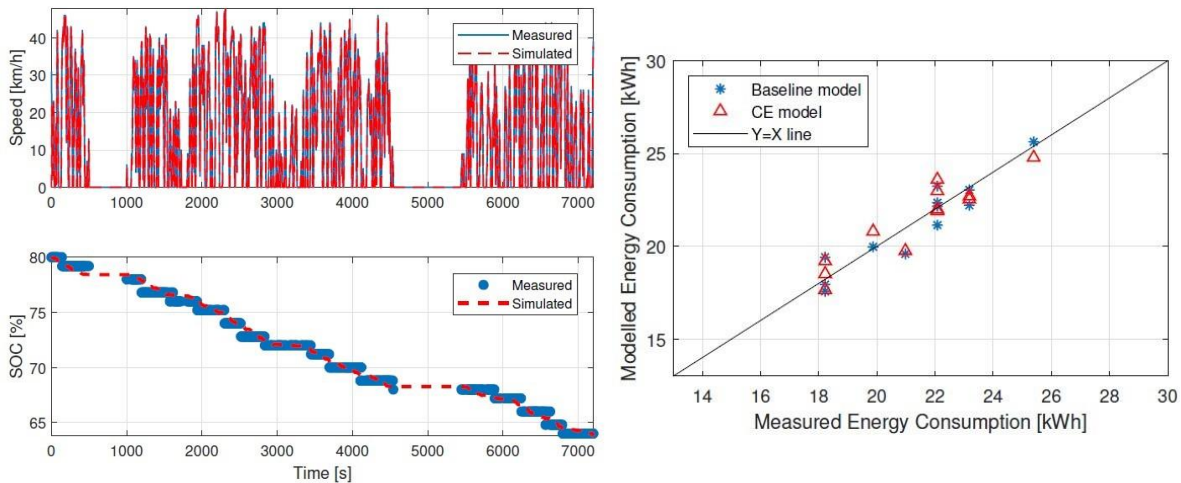


Figure G.4: Validation results for the baseline electric bus model.

G.2 Methodology

G.2.1 Journey selection and definition

A subset of journeys was identified from the various journey databases available to the project team, which represented interesting ‘edge cases’ to study in more detail. The journeys are summarised in Table G.2. Journeys from each of the three important journey types (warehouse-to-warehouse, multi-drop, and tramping) were included. The Andover (logistics depot) scenario is unique in that the data represents an actual log of a lorry journey from a specific day, and so the stop durations are known precisely. This scenario will be used as an illustrative scenario throughout this section; it’s journey reconstruction is shown in Figure G.5. In all other cases only drop-off locations are known, and here a 20-minute drop-off stop was assumed. In all cases, a full battery state of charge was assumed at departure.

Journey type	Origin	Drop-off stops	Destination
Warehouse-to-warehouse	Swindon (Cheney Manor Industrial Estate)	N/A	Newton Aycliffe (warehouse)
	Royal London Hospital	N/A	Wath-upon-Deane (warehouse)
Multi-drop	Andover (logistics depot)*	Lymington, Romsey, Andover, Yeovil, Ongar	Andover (logistics depot)
	Aylesford (retail distribution)	Eastbourne, Lewes, Marylebone	Aylesford (distribution centre)
	Aylesford (retail distribution)	Bloomsbury, Kensington Gardens, Ramsgate	Aylesford (distribution centre)
	Aylesford (retail distribution)	Saxmundham, Woodbridge, Kingston-upon-Thames	Aylesford (distribution centre)
Tramping	Tirril	Shap, Bolton, Buxton, St Ives (Cambs), Newton Stewart, Girvan, Irvine (over 2 days)	Tirril

* Actual drop-off stop durations known from vehicle log.

Table G.2: Journeys considered in the study.

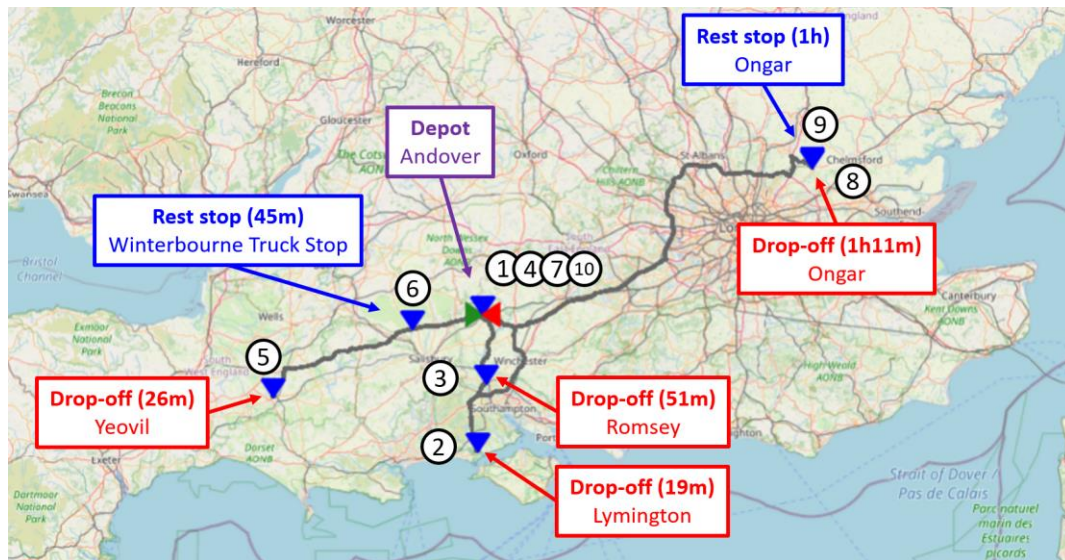


Figure G.5: Sample journey reconstruction (Andover logistics depot journey).

Driver rest stops were added to all journeys in accordance with UK/EU driver hour regulations which require “a break or breaks totalling at least 45 minutes after no more than 4 hours 30 minutes driving”. After 4h30m of driving time (i.e., excluding time during stops), a 45-minute rest stop was added at a reasonable location near the route in question. A variation of this was also analysed, with 30-minute rest stops every 2h15m in line with the permissible split-break allowances. In the tramping journey, an overnight rest stop was included after nine hours of driving in line with the prescribed driving hour limits, and it was assumed that the battery was fully charged by departure time the next day. Although it is possible for drivers to rest during drop-off stops, it was assumed for these simulations that the driver was still ‘working’ during these stops (i.e., helping to unload etc.) and so rest time was only accumulated at the dedicated rest stops.

The conventional rest stop locations for the Andover logistics depot journey are shown in Figure G.6 (left). These are in line with the 4h30m driving time requirements, though the second stop is 1 hr where it only strictly needs to be 45 min. The alternative split break rest stop strategy for this journey results in four simulated 30-minute rest stops, as illustrated in Figure G.6 (right). This adds 15 minutes to the total journey time of around 15 hours. Although the total driving time of this journey exceeds 9 hours, we know in this case that there is a driver change at the depot stop (stop #7 in Figure G.5).

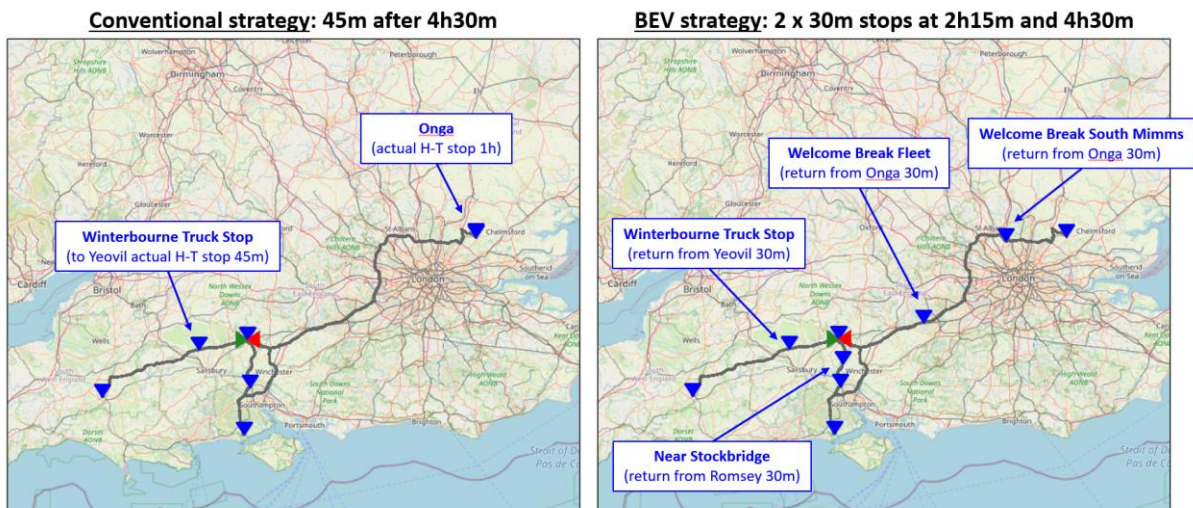


Figure G.6: Conventional and 'BEV' rest stop strategies.

G.3 Scenarios

Each journey was simulated against a four ERS configurations and four static charging scenarios, giving up to 16 scenario combinations per journey. These are detailed as follows.

ERS scenarios:

- No ERS: No ERS infrastructure is available: a 'full battery electric' scenario.
- ERS 'Light': The 'Light' ERS topography is available, covering approximately 3300 km of the UK road network (in both directions).
- ERS 'Medium': The 'Medium' ERS topography is available, covering approximately 4800 km of the UK road network (in both directions).
- ERS 'Heavy': The 'Heavy' ERS topography is available, covering approximately 7000 km of the UK road network (in both directions).

Static charging scenarios:

- No static charging: Lorries only have access to 'low-power' charging at their depot, where they can typically fully charge overnight.
- Drop-off charging: 'High-power' charging is available at any drop-off point such as warehouses and retail outlets, at which the lorry can charge while stopped.
- Rest stop charging: 'High-power' charging is available at public lorry stops/charging facilities, at which the lorries can stop during the driver's mandatory 45-minute rest after 4h30m of driving.
- 'BEV rest stop charging': A variation of the above scenario, where drivers choose to stop for 30-minute rests every 2h15m in line with the permissible split-break allowances. This is a more favourable stop strategy for battery electric vehicles.

The three ERS topographies are shown in Figure G.7. Also shown is a representative distribution of 300 public static charger sites, with density of chargers approximately proportional to regional population density. It is worth emphasising that the site locations are representative of regional distribution, and do not suggest specifically chosen locations on specifically chosen roads. For this reason, the rest stop locations used for the journey simulations are based purely on driving time, but we will see later how these resultant locations compare with the representative charger distribution map.

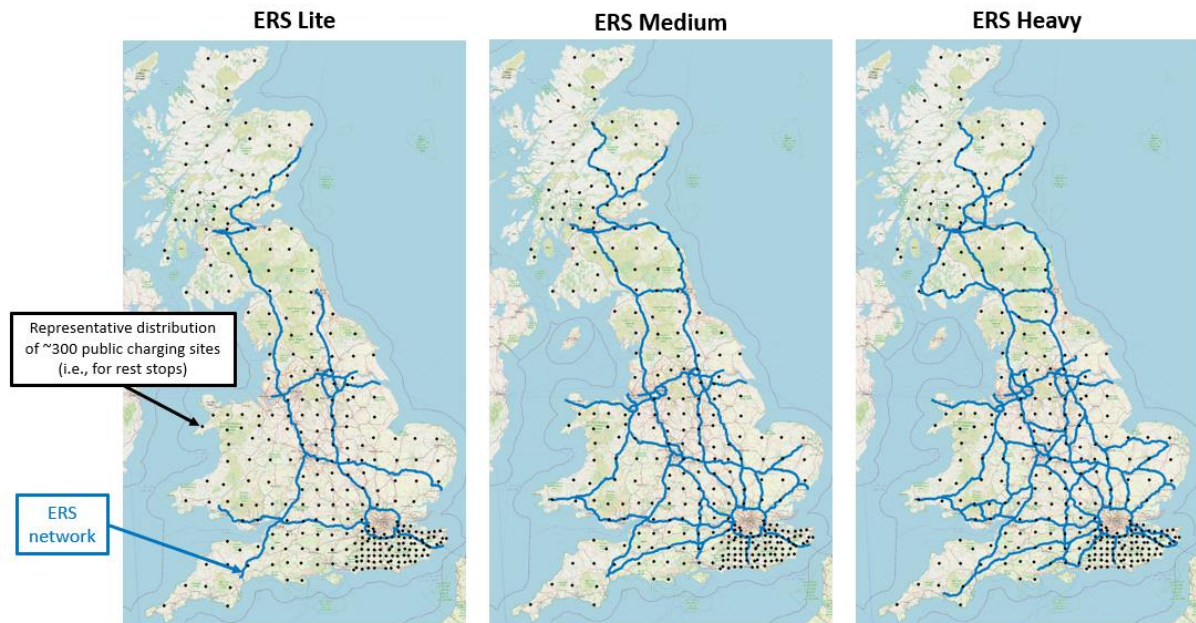


Figure G.7: ERS Light, Medium and Heavy topographies, overlaid on a representative distribution of 300 public static charging sites.

For the Andover logistics depot journey, the four ERS scenarios result in noticeably different proportions of the journey having access to ERS charging. ERS 'Light' adds catenary charging to the second leg of the journey, while ERS 'Medium' and 'Heavy' cover most of the journey kilometres. This is illustrated in Figure G.8. Drive cycle results from the ERS Light and Heavy scenarios are given in Figures G.9 and G.10 to demonstrate the impact of the extent of the ERS network. (Both are shown for the case of the BEV rest stop static charging scenario.)

By simulating each of the scenarios, a matrix of battery sizes can be generated as shown in Table G.3. ERS topographies are shown on the x-axis, and static charging scenarios on the y-axis. The individual cells are colour-coded for easy inference of the impact which each of the scenarios makes, with green for smaller batteries, and red for bigger batteries. The impact of additional ERS infrastructure and additional static charging opportunities on reducing the necessary battery sizes is clear.

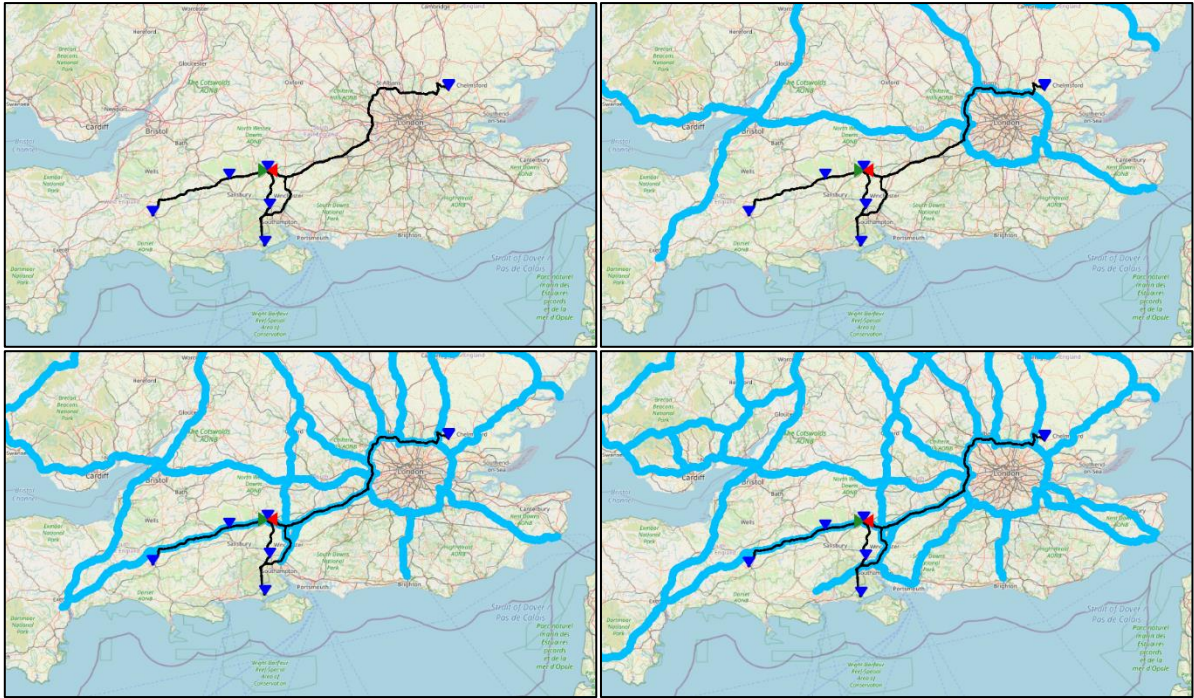


Figure G.8: The Andover logistics depot scenario with the four ERS scenarios: No ERS (top left), ERS Light (top right), ERS Medium (bottom left), and ERS Heavy (bottom right).

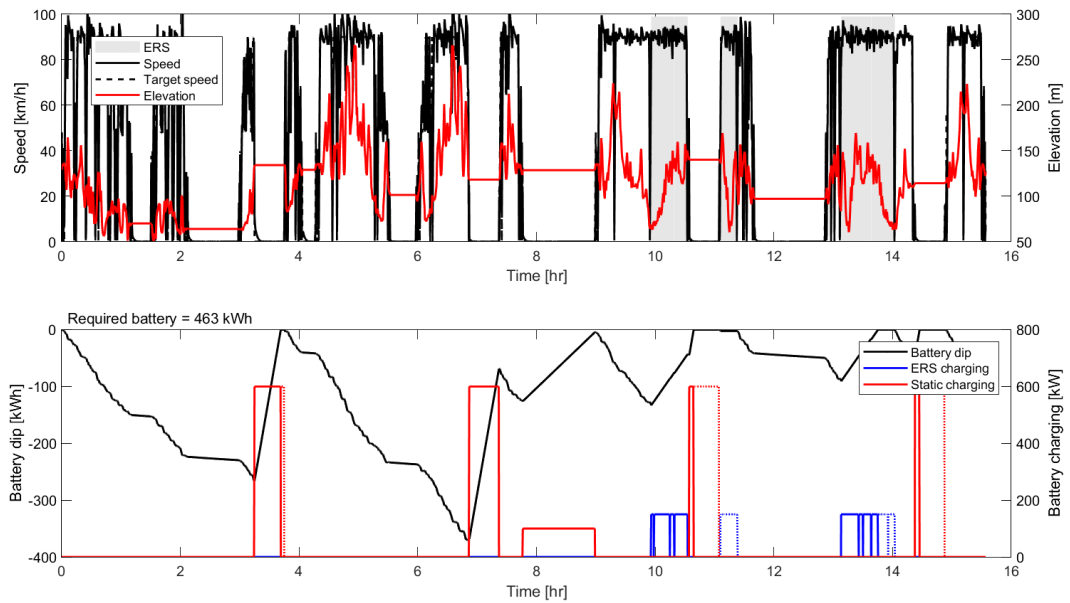


Figure G.9: Andover logistics depot drive cycle (ERS Light + BEV rest stop charging).

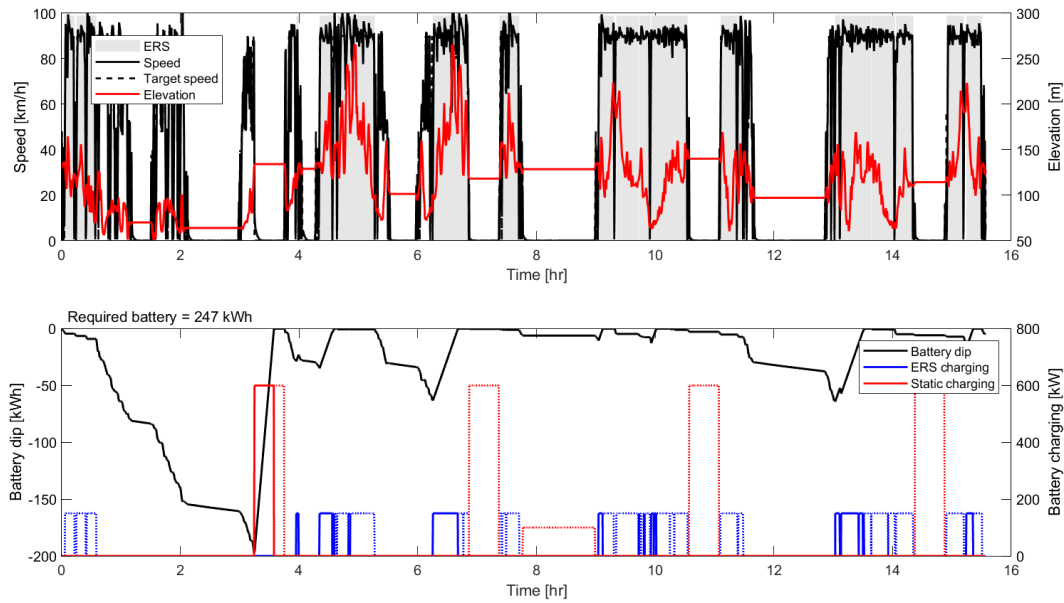


Figure G.10: Andover logistics depot drive cycle (ERS Medium + BEV rest stop charging).

Andover logistics depot	Required battery capacity (kWh)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	1503	880	290	224
Charge at drop-off sites (600 kW)	479	337	103	88
Charge at public rest stops (600 kW, 45m)	794	794	290	224
Charge at public rest stops (600 kW, 30+30m)	463	463	247	182

Table G.3: Andover logistics depot – summary of results.

G.4 Results overview

In this section, a high-level overview of the results is given, with a focus on the resultant battery capacity requirements from each of the up-to-16 scenarios per journey studied. Each summary of results is presented as a table, with ERS topography scenarios on the columns, and static charging scenarios in the rows. The resultant routes are also shown for each journey, overlaid on the ERS 'Light' configuration for illustrative purposes. The green marker shows the journey start, the red marker the journey end, and the blue markers the stops (both drop-off and rest stops). For each journey the stops are shown for both the conventional rest stop strategy, and the 'BEV rest stop' strategy for comparison.

G.4.1 Warehouse to warehouse

The Swindon to Newton Aycliffe journey is summarised in the figure and table below. There are no drop-off stops in this instance, hence the 'charge at drop-off sites' scenario is not applicable. There is one conventional rest stop around York, and an additional rest stop near Birmingham in the BEV rest stop strategy.



Figure G.11: Swindon to Newton Aycliffe route (conventional rest stops left, BEV rest stops right) (ERS Light).

Swindon to Newton Aycliffe	Required battery capacity (kWh)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	908	181	129	129
Charge at drop-off sites (600 kW)	N/A	N/A	N/A	N/A
Charge at public rest stops (600 kW, 45m)	755	181	129	129
Charge at public rest stops (600 kW, 30+30m)	411	129	129	129

Table G.4: Swindon to Newton Aycliffe – summary of results.

The Royal London to Wath Dearne journey is summarised in the figure and table below. There are no drop-off stops in this instance, hence the ‘charge at drop-off sites’ scenario is not applicable. Further, the total driving time in this journey is less than 4.5 hours, hence there is no conventional rest stop charging scenario either. However, the BEV rest stop strategy introduces one 30-minute rest stop.

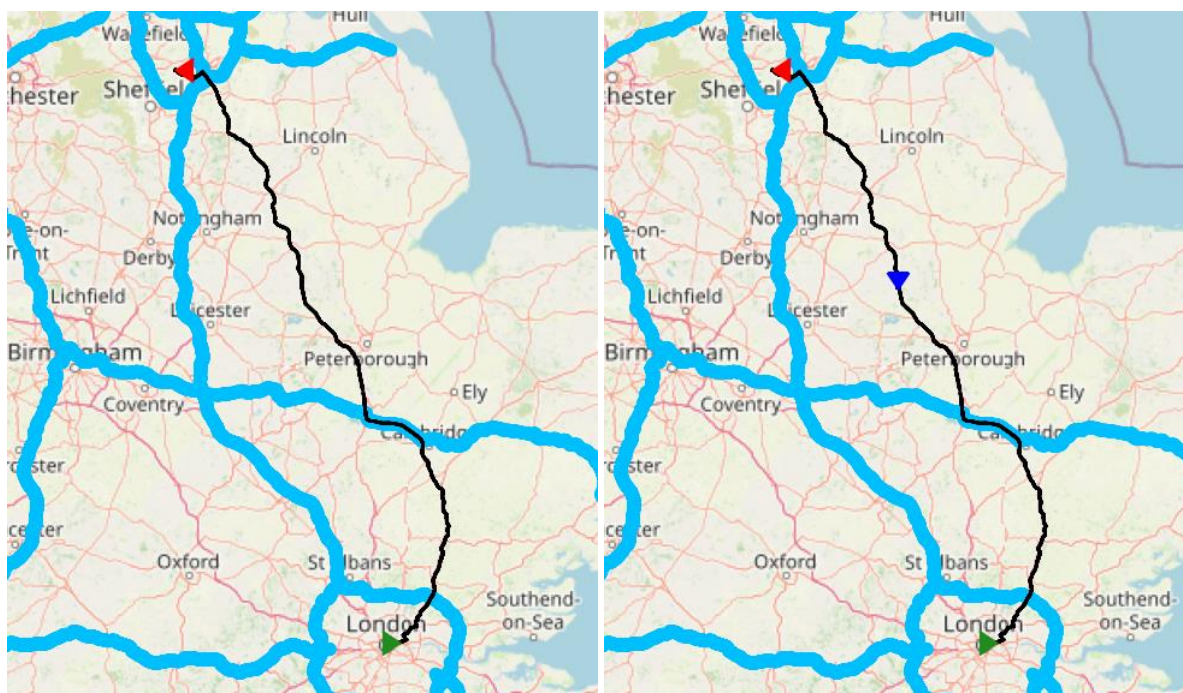


Figure G.12: Royal London to Wath Dearne route (conventional rest stops left, BEV rest stops right) (ERS Light).

Royal London to Wath Dearne	Required battery capacity (kWh)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	599	502	71	71
Charge at drop-off sites (600 kW)	N/A	N/A	N/A	N/A
Charge at public rest stops (600 kW, 45m)	N/A	N/A	N/A	N/A
Charge at public rest stops (600 kW, 30+30m)	382	297	71	71

Table G.5: Royal London to Wath Dearne – summary of results.

G.4.2 Multi-drop

The Andover logistics depot journey is summarised below. There are two rest stops in the conventional rest stop strategy, and four 30-minute rest stops in the BEV rest stop strategy.



Figure G.13: Andover logistics depot route (conventional rest stops left, BEV rest stops right) (ERS Light).

Andover logistics depot	Required battery capacity (kWh)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	1503	880	290	224
Charge at drop-off sites (600 kW)	479	337	103	88
Charge at public rest stops (600 kW, 45m)	794	794	290	224
Charge at public rest stops (600 kW, 30+30m)	463	463	247	182

Table G.6: Andover logistics depot – summary of results.

The Aylesford Eastbourne (retail) journey is summarised below. The journey requires less than 4.5 hours driving time, and so there are no conventional 45-minute rest stops. One 30-minute rest stop is introduced near Burgess Hill under the BEV rest stop strategy.

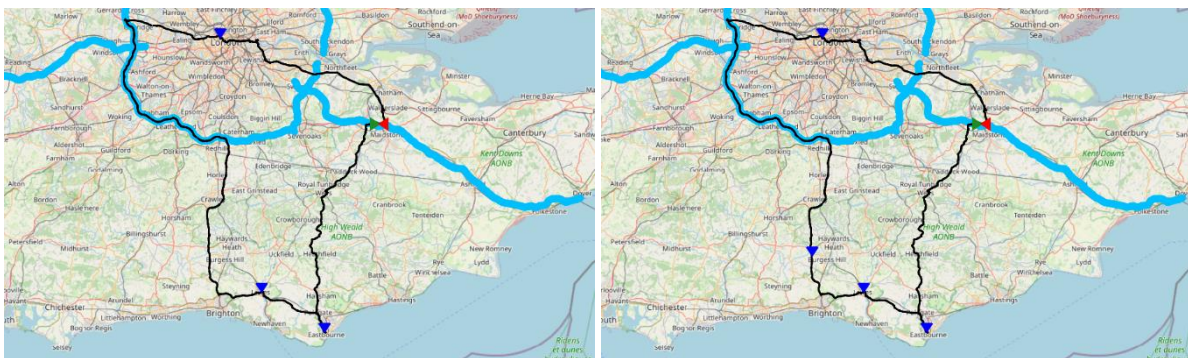


Figure G.14: Aylesford Eastbourne (retail) route (conventional rest stops left, BEV rest stops right) (ERS Light).

Aylesford Eastbourne (retail)	Required battery capacity (kWh)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	818	588	366	342
Charge at drop-off sites (600 kW)	336	226	223	223
Charge at public rest stops (600 kW, 45m)	N/A	N/A	N/A	N/A
Charge at public rest stops (600 kW, 30+30m)	454	373	342	342

Table G.7: Aylesford Eastbourne (retail) – summary of results.

The Aylesford Bloomsbury (retail) journey is summarised below. The journey requires less than 4.5 hours driving time, and so there are no conventional 45-minute rest stops. One 30-minute rest stop is introduced near Gravesend under the BEV rest stop strategy.



Figure G.15: Aylesford Bloomsbury (retail) route (conventional rest stops left, BEV rest stops right) (ERS Light).

Aylesford Bloomsbury (retail)	Required battery capacity (kWh)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	709	700	684	268
Charge at drop-off sites (600 kW)	314	314	310	97
Charge at public rest stops (600 kW, 45m)	N/A	N/A	N/A	N/A
Charge at public rest stops (600 kW, 30+30m)	406	397	387	199

Table G.8: Aylesford Bloomsbury (retail) – summary of results.

The Aylesford Saxmundham (retail) journey is summarised below. The single 45-minute rest stop and two 30-minute rest stops occur around the same locations as existing drop-off stops.

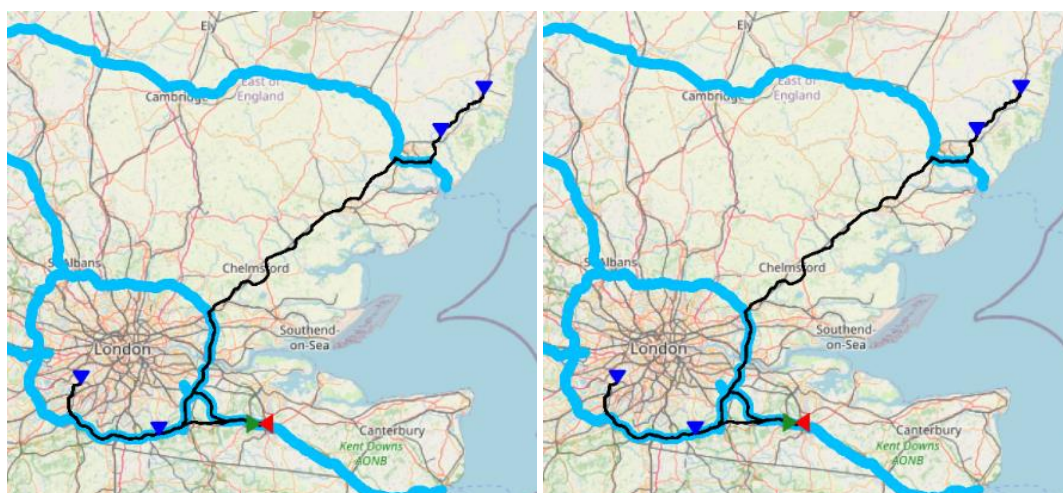


Figure G.16: Aylesford Saxmundham (retail) route (conventional rest stops left, BEV rest stops right) (ERS Light).

Aylesford Saxmundham (retail)	Required battery capacity (kWh)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	1148	492	181	181
Charge at drop-off sites (600 kW)	465	233	87	87
Charge at public rest stops (600 kW, 45m)	847	492	181	181
Charge at public rest stops (600 kW, 30+30m)	473	257	93	93

Table G.9: Aylesford Saxmundham (retail) – summary of results.

G.4.3 Tramping

The two-day Tramping journey was assessed as two separate journeys, with the overnight stop chosen to coincide with 9 hours of driving time. The resulting overnight stop was near Leeds. The Day 1 journey is summarised below, with the red marker indicating the final destination for the day at the overnight stop. This journey includes either a single 45-minute stop, or three 30-minute stops throughout the 9 hour journey.

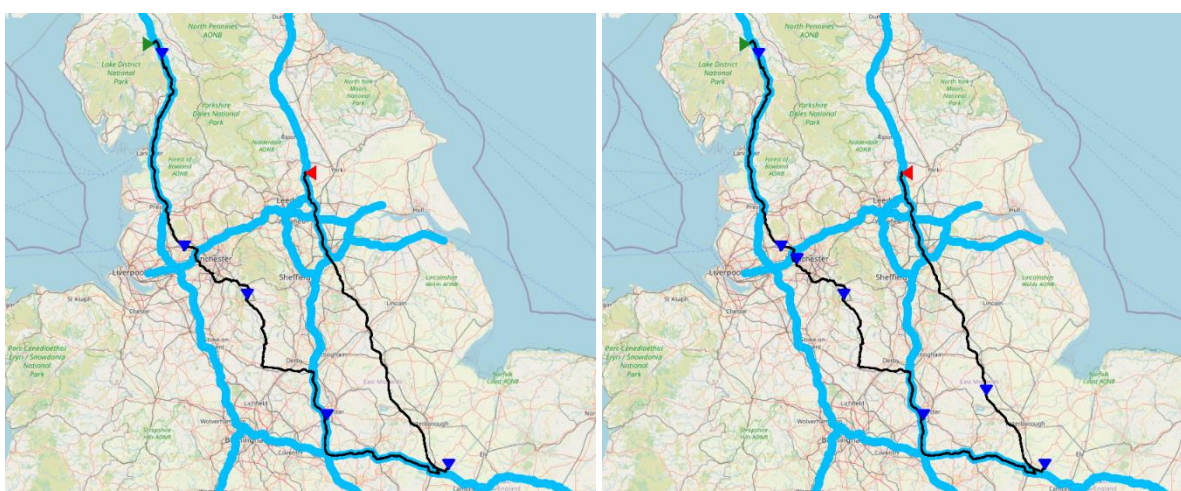


Figure G.17: Tramping Day 1 route (conventional rest stops left, BEV rest stops right) (ERS Light).

Tramping Day 1	Required battery capacity (kWh)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	1479	573	367	224
Charge at drop-off sites (600 kW)	718	357	167	122
Charge at public rest stops (600 kW, 45m)	910	429	367	224
Charge at public rest stops (600 kW, 30+30m)	436	315	292	226

Table G.10: Tramping Day 1 – summary of results.

The Day 2 journey is summarised below, with the green marker indicating the origin at the overnight stop. This journey again includes either a single 45-minute stop, or three 30-minute stops throughout the 9 hour journey.



Figure G.18: Tramping Day 1 route (conventional rest stops left, BEV rest stops right) (ERS Light).

Tramping Day 2	Required battery capacity (kWh)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	1436	1011	1011	384
Charge at drop-off sites (600 kW)	675	377	377	252
Charge at public rest stops (600 kW, 45m)	866	544	544	290
Charge at public rest stops (600 kW, 30+30m)	399	361	361	152

Table G.11: Tramping Day 2 – summary of results.

G.4.4 Summary

A number of observations can be made from the above journey simulation results:

1. Without ERS or static chargers at drop-offs or rest stops, battery sizes of up to 1,500 kWh would be required to fulfil these journeys. The most challenging cases in this respect are the tramping journeys, and the Andover logistics depot case. Although a shorter journey, the Andover case is difficult due to the brief stop and driver change at the depot, which doesn't allow much time for recharging.

2. The addition of any degree of ERS reduced these battery size needs significantly, depending on the journey and which parts of the road network it utilises.
3. For all ERS scenarios, the 'BEV rest stop' strategy consistently yields smaller battery requirements than the conventional rest stop strategy, by close to 50% in some cases, with only a small increase in journey time.
4. An ERS 'Light' configuration, coupled with a network of public rest stop chargers and a BEV rest stop strategy, results in battery capacity requirements less than 500 kWh. In some instances, such as the Swindon to Newton Aycliffe journey, requires a battery of only 130 kWh due to the use of main arterial roads which are covered by the ERS Light configuration.

G.5 Other Observations

G.5.1 Rest stop static charger locations

As described earlier, the rest stop locations in the simulations were determined purely on the basis of driving time, as the actual locations of future public static charging sites are not known. Where possible, a nearby fuel station or actual lorry stop site was chosen in the simulations for rest stops. However, the illustrative public static charger distribution can be used to check how reasonable such an assumption is, by comparing our theoretical stop locations with those distributed by the illustrative map (representing around 300 static charger locations nationally). We now consider four case studies to assess this assumption: two in the South East with a relatively dense charger network (Aylesford-Eastbourne and Aylesford-Saxmundham), and two in the North West with a less dense charger network (Tramping Day 1 and Day 2).

The two South East retail distribution scenarios are shown in Figures G.19 and G.20, for the 'BEV rest stop' strategy which gives rise to the most rest stops. The representative static charger map is now superimposed on the map, as represented by the grey dots. The ERS Light network is shown for illustrative purposes. The simulated rest stop and its nearest static charger site from the representative static charger map are circled in red. In these cases, the stops are very close (< 5 km) from the theoretical stop locations, meaning that the required detour or early/late stop relative to driving time would not significantly affect the battery size results at all. The approximate distribution of chargers in this region is 10x10 km, which means that a vehicle would never be further than 6 km (as the crow flies) from a charging point. In terms of vehicles kilometres, assuming a distance of 10 km to the nearest charging point, means a need for around 20 kWh additional battery capacity compared to the theoretical case.

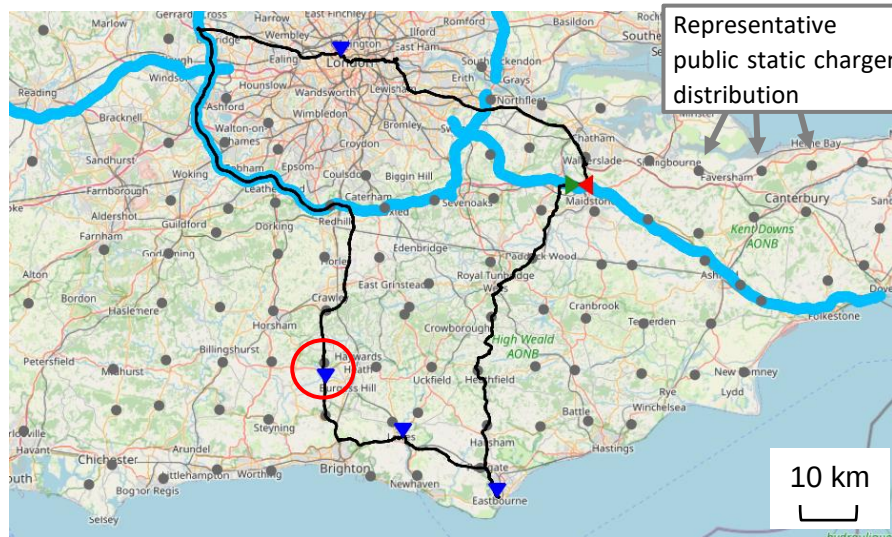


Figure G.19: Aylesford Eastbourne (retail).

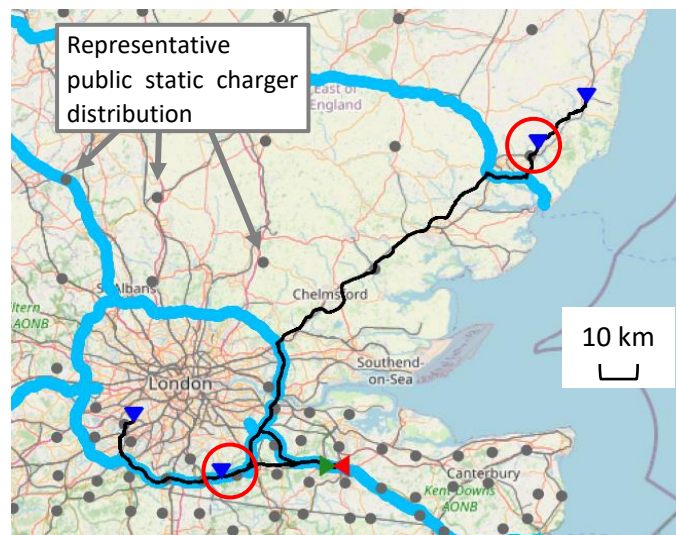


Figure G.20: Aylesford Saxmundham (retail).

The two North West tramping scenarios are shown in Figures G.21 and G.22, again for the 'BEV rest stop' strategy which gives rise to the most rest stops. The ERS Light network is shown for illustrative purposes. The simulated rest stop and its nearest static charger site from the representative static charger map are circled in red. In the Day 1 scenario, the distance between simulated and theoretical rest stops are 10-15 km (as the crow flies). In the case of the first stop (top left), the required detour would follow an ERS section of the road network, and so the vehicle would not suffer any battery capacity penalty, but would suffer a small time penalty. For the second stop, the simulated and theoretical stops take place on the ERS network, meaning that an earlier stop would not suffer any battery capacity penalty. The final theoretical stop would require an earlier stop than has been simulated, but because the vehicle reaches the ERS network for the last part of the journey, the required battery capacity would not be impacted in this case.

In the Day 2 scenarios, the differences in simulated and theoretical rest stop locations are even smaller, and so are not expected to have a significant impact on the calculated battery capacity requirements. The static charger density in this region is approximately 35x35 km. At

worst, this means a charger might be 25 km away from the ideal rest stop location, resulting in an additional ~50 kWh requirement on the battery. This is 10% of a 500 kWh battery's capacity, which could, if needed, be utilised from the battery's lowest 20% state of charge on occasion without significant impact on the battery's longevity.

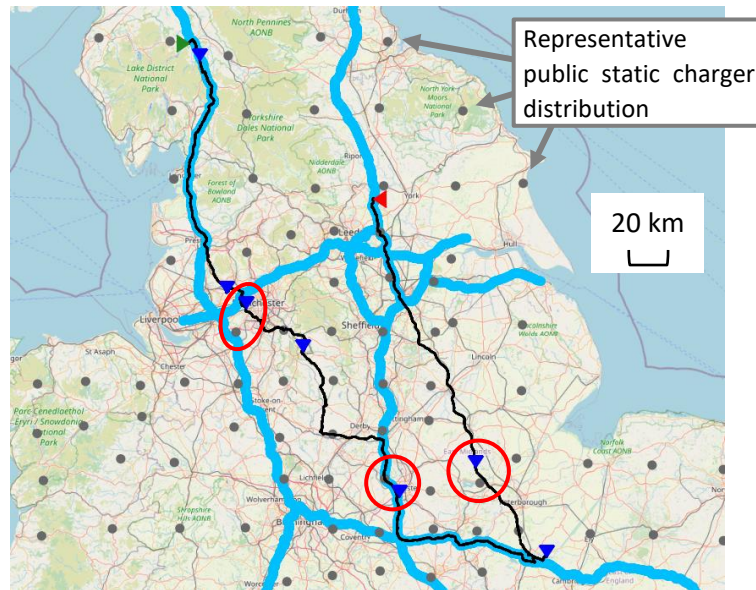


Figure G.21: Tramping Day 1.



Figure G.22: Tramping Day 2.

G.5.2 Energy consumption

The total vehicle energy consumption was recorded for each journey, which is a function of both vehicle parameters (such as mass, rolling resistance, aerodynamic drag co-efficient, auxiliary power) and journey parameters (elevation profile, posted speed limits, number of stop-start manoeuvres). The average energy consumption per kilometre is a useful metric, which is required for use in the large-scale agent-based modelling (ABM) simulations. The results over the full range of journey scenarios are given in Figure G.23. For a fixed journey,

the consumption is approximately the same for the various scenarios but increased slightly for the 'BEV rest stop' strategy scenarios owing to the additional stop-start manoeuvres for each rest stop. The results range from 1.65 kWh/km to 2.10 kWh/km, with an average of 1.88 kWh/km.

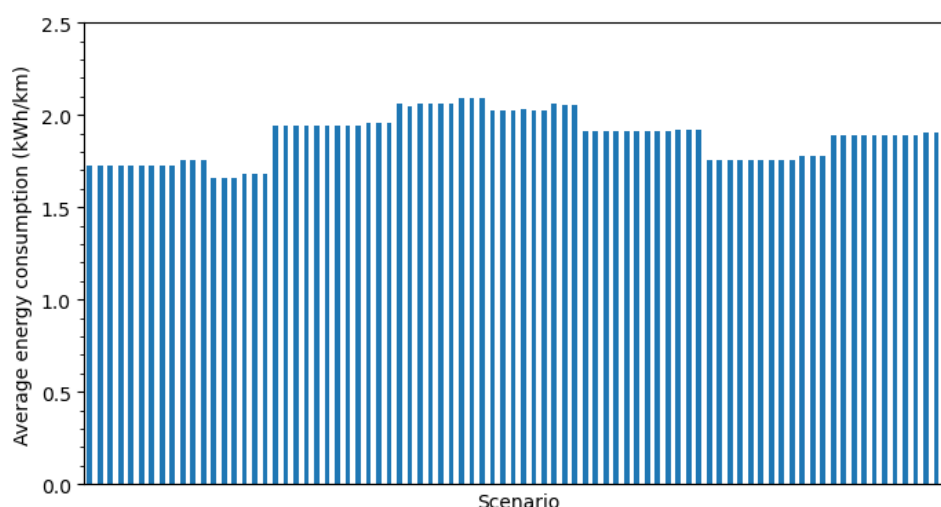


Figure G.23: Average energy consumption per scenario

It is also useful to demonstrate the typical vehicle power demands on a flat section of motorway at a constant speed, for the given vehicle assumptions. This can be used to inform power supply demands for the ERS system. Table G.12 shows a summary of the power demand of the vehicle at steady speeds for a range of vehicle masses and vehicle speeds. At the maximum permitted speed of 96 km/h for lorries in the UK, the steady power consumption is 144 kW.

Speed (km/h)	Vehicle mass (tonnes)					
	34	36	38	40	42	44
10	11	11	12	12	13	13
20	18	18	19	20	21	21
30	25	26	27	28	29	30
40	34	35	37	38	39	41
50	44	46	48	50	51	53
60	57	59	61	63	65	68
70	72	75	77	80	82	85
80	90	93	96	99	102	105
90	112	115	119	122	125	128
96	127	131	134	137	141	144
100	138	142	145	149	152	156
110	168	172	176	180	184	188
120	203	207	211	216	220	224

Table G.12: Theoretical vehicle power consumption on a flat road as a function of mass and speed

G.5.3 Embodied carbon

The tables below summarise the embodied carbon in each of the ERS vehicle configurations which result from the above scenarios, using the same visualisation approach as before. A

carbon intensity for the batteries of 100 kg/kWh has been assumed as before. The trends are linearly correlated with the battery sizes as expected, with more ERS and additional static charging capacity resulting in a notable reduction in embodied carbon due to reduced battery size needs.

Swindon to Newton Aycliffe	Vehicle embodied carbon (t CO2)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	143	71	65	65
Charge at drop-off sites (600 kW)	N/A	N/A	N/A	N/A
Charge at public rest stops (600 kW, 45m)	128	71	65	65
Charge at public rest stops (600 kW, 30+30m)	94	65	65	65
Royal London to Wath Dearne	Vehicle embodied carbon (t CO2)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	112	103	60	60
Charge at drop-off sites (600 kW)	N/A	N/A	N/A	N/A
Charge at public rest stops (600 kW, 45m)	N/A	N/A	N/A	N/A
Charge at public rest stops (600 kW, 30+30m)	91	82	60	60
Andover logistics depot	Vehicle embodied carbon (t CO2)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	203	141	82	75
Charge at drop-off sites (600 kW)	100	86	63	61
Charge at public rest stops (600 kW, 45m)	132	132	82	75
Charge at public rest stops (600 kW, 30+30m)	99	99	77	71
Aylesford Eastbourne (retail)	Vehicle embodied carbon (t CO2)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	134	111	89	87
Charge at drop-off sites (600 kW)	86	75	75	75
Charge at public rest stops (600 kW, 45m)	N/A	N/A	N/A	N/A
Charge at public rest stops (600 kW, 30+30m)	98	90	87	87
Aylesford Bloomsbury (retail)	Vehicle embodied carbon (t CO2)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	123	123	121	79
Charge at drop-off sites (600 kW)	84	84	84	62
Charge at public rest stops (600 kW, 45m)	N/A	N/A	N/A	N/A
Charge at public rest stops (600 kW, 30+30m)	93	92	91	72
Aylesford Saxmundham (retail)	Vehicle embodied carbon (t CO2)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	167	102	71	71
Charge at drop-off sites (600 kW)	99	76	61	61
Charge at public rest stops (600 kW, 45m)	137	102	71	71
Charge at public rest stops (600 kW, 30+30m)	100	78	62	62

Tramping Day 1	Vehicle embodied carbon (t CO ₂)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	200	110	89	75
Charge at drop-off sites (600 kW)	124	88	69	65
Charge at public rest stops (600 kW, 45m)	144	95	89	75
Charge at public rest stops (600 kW, 30+30m)	96	84	82	75
Tramping Day 2	Vehicle embodied carbon (t CO ₂)			
	ERS topography			
	None	Lite	Medium	Heavy
No static charging	196	154	154	91
Charge at drop-off sites (600 kW)	120	90	90	78
Charge at public rest stops (600 kW, 45m)	139	107	107	82
Charge at public rest stops (600 kW, 30+30m)	92	89	89	68

Table G.13: ERS vehicle combination embodied carbon (all journeys shown).

G.6 Conclusions

1. A detailed vehicle-level simulation tool was developed to study individual journeys. Edge-case warehouse to warehouse, multi-drop and tramping journeys were analysed against a range of ERS scenarios (no ERS, ERS Light, ERS Medium and ERS Heavy) and static charging scenarios (no static charging, charging at drop-off stops, and charging at rest stops with two rest stop strategies).
2. While the journeys would otherwise require battery capacities of up to 1,500 kWh to complete, ERS has been shown to significantly decrease these battery size needs, with further reductions from a moderate distribution of public chargers for use during rest stops. An ERS Light configuration with a moderate distribution of public charging sites (around 300 nationally) yields a battery requirement ranging from 130 kWh to a maximum of 500 kWh. The impact of this on reducing embodied carbon in the vehicles has also been demonstrated. Furthermore, in practice, the addition of ERS may reduce the stop time required at public charging points.
3. A moderate distribution of around 300 national charging sites, distributed approximately evenly with a density correlated with regional population density, has been shown to yield sufficient charging sites to coincide with the rest stop needs of the journeys studied.
4. Additional charging facilities at drop-off locations (i.e., at retail outlets or warehouses) would further reduce the battery capacity needs if available.
5. The energy demands of a 44 t lorry combination with some auxiliary loads on these journeys range from 1.65 kWh/km to 2.10 kWh/km, with an average of 1.88 kWh/km. Steady, flat motorway driving at the maximum allowable speed of 96 km/h yields a power demand of 144 kW per vehicle.

Appendix H – Funding

This appendix sets the scene with respect to some of the issues which will influence the way in which the ERS project will be delivered and funded. It is based on a number of discussions with various relevant parties and their thoughts and comments have been included here. The list of the parties consulted may be found at the end of this appendix.

ERS will become a critical component of the UK Government's decarbonisation plans. Users will be encouraged and facilitated in achieving their own decarbonisation goals with the common purpose to meet the 2050 Net Zero deadline. The delivery and operation of ERS will meet leading ESG standards and ensure that all stakeholders are comfortable with the outcomes. Importantly investors and stakeholders will be keen to see the bar set high for ESG metrics and closely monitored on a continual basis to ensure they are maintained and improved whenever possible. The benefits will be monitored and measured at a national level.

The objectives of ERS are at the heart of the SDGs set by the United Nations in 2015, summarised below. Many of the SDGs may not seem fully relevant to a UK situation but this is a global effort agreed by the UN and the contribution of the UK across all SDGs is important.



Figure H.1: UN sustainable development goals.

ERS contributes to most of the SDGs to greater or lesser extent however three SDGs directly identify against ERS including: SDG7 Affordable and Clean Energy, SDG8 Good Jobs and Economic Growth and SDG13 Climate Action. Simply put, all energy supplied and distributed through ERS will be from renewable sources feeding a solution that will create highly skilled jobs while offering the lowest cost for the movement of heavy goods across the UK road network. Low-cost efficient distribution of goods of whatever description will be

passed on to everyone using the transportation supply chain and will benefit the economy while the resulting decarbonisation will improve the climate for all.

H.1 Project Finance and Funding

H.1.1 Funding the Solution

The overall cost of ERS is estimated to be £20 billion and will demand considerable expertise to put the necessary finance in place. The involvement of the UK Government will be required in a number of aspects. The degree to which this occurs financially will be dependent on perceived project risk and the need for mitigation to encourage private investment if a private route is to be chosen.

There are two parts to ERS, first the catenary wire system to provide energy along major highways and second, static charge points that will need to be positioned to serve HGVs once they need to leave the main highways.

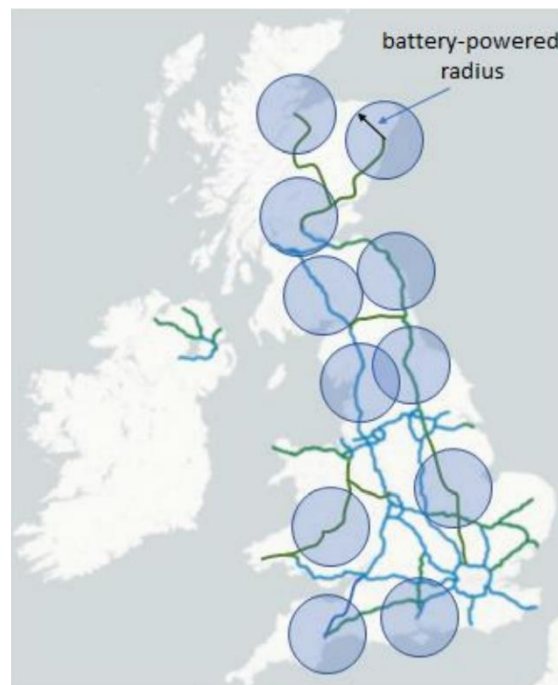


Figure H.2: An example representation of an ERS network supported by several static charging stations, adapted from Ainalis et al. (2020).

H.1.2 Static Charge Points

The main focus of this report is regarding the greater complexities of providing the catenary system along main highway routes, however, static charge points form part of a national network for HGVs travelling beyond the catenary system. Static charge points for HGVs could be financed and delivered in a similar manner to current electric vehicle (EV) charging serving cars and vans. Government support has been provided to assist EV owners and businesses with vehicle charging at home and at work, as well as through local authorities. EV charging at a national scale with 50kW and above charge points is being driven by the private sector. This is often facilitated by estate managers, landowners and retail where vehicle charging coincides with encouraging dwell time and footfall at particular locations. This is fine for cars in an existing car park but not for free access of large numbers of HGVs.

There could be an opportunity for private entities, working within the vehicle charging sector, to develop locations to accommodate charging electric HGVs and provide appropriate service facilities during dwell times. Obtaining sufficient land area in a convenient location with adjacent grid capacity is a concern when creating these locations for car and van charging but for HGVs there is a greater degree of difficulty due to scale. Discussions with the private sector to date have shown great interest in providing charging locations for electric HGVs but the model is dependent on utilisation and possible involvement of adjacent retail services such as food, beverage and accommodation. To ensure some controls are exerted on the rollout of static charge points general locations could be identified and interested providers be required to competitively tender for the right to provide charging services within specific performance standards.

H.1.3 The Catenary System

For the catenary system, several alternative models of ownership and financial involvement exist and have been examined. Publicly owned solutions for national infrastructure which include Network Rail and National Highways and privately owned solutions including utility companies. An example of the latter is the Thames Tideway Tunnel (TTT) which, without the UK Government standing behind the major non-financeable risks, private investors would not likely be participating. Whether the ERS solution will become a publicly owned solution or a private one will be dependent on the level of risk and available mitigation measures.

Regarding nationally owned nationwide transportation infrastructure, Network Rail and National Highways models are considered successful and rely mostly on Government funding from its tax base. However, over time, consideration has been given to privatisation models for most classes of public assets with the degree of private sector involvement varying across different solutions. One model which has continued in private ownership over the past thirty years is the regulated utility model and there are several privately owned utility models in the UK including water, gas, electricity and telecommunications.

When considering public and private alternatives HS2 is noteworthy in that it has had to be publicly funded although some kind of PPP was initially being considered. HS2 is still not considered a proven concept and it will not be known for some time whether it is actually a good idea. Government has possibly lost some credibility with the cancellation of the eastern leg so can Government commitment today be relied upon for tomorrow with the rollout of national infrastructure. The possibility of an incomplete ERS network will certainly not encourage the take up of a national catenary system by users. Despite Government changes and changes in policy over time which can undermine long term strategies, a fully public solution will likely be cheaper. If ERS is publicly funded with the Government taking on the risks there will be no requirement for private sector dividends or rewards. However, the Government is very much in debt due to Covid (and other matters) and the cost of the Government debt is going up due to interest rate changes which are expected to increase this year and next. The Government might be incentivised to pursue a privately funded solution.

When deciding the extent of public or private involvement the matter of risk allocation should form part of the decision-making process. Clearly the Government must stand behind the uninsurable risks for the benefit of the nation as a whole but other project risks could be arguably better handled by the private sector. This follows the basic principle of allocating risks to those best able to deal with them. The private sector is better placed and nimbler to deal with certain project and delivery risks which it can cope with under its full control. Other risks which the private sector could not have full control over and some risks which cannot be insured must remain with Government.

The issue of private ownership and private sector involvement in public assets has become politicised, and it is not the intent here to argue about the merits of private versus public ownership of infrastructure serving the public but merely to present solutions which have a precedent and are considered viable.

H.2 Project Risks

In respect of both public and private ownership of this high value national ERS infrastructure, the UK Government is a necessary common denominator as underwriter of the uninsurable risk elements. Given the significant contribution that electrification of transportation makes towards achieving the 2050 Net Zero targets, the UK Government will likely be very keen to play a significant part in successful delivery of the solution. The Government should be an active player and supporter whether to ensure the passing of appropriate legislation and policy to facilitate the delivery and operation of ERS or as the insurer of last resort or providing funds to make the necessary reinforcements to the grid. The degree of involvement of the Government in the final solution may be determined by whether it will provide any direct funding, apart from the demonstrator project, and the degree of risk that is envisioned in the project. Whether ERS is publicly or privately funded may also be dependent on the political persuasion of the Government in power at the time decisions are made.

The ability to understand and manage project risk is critical whether ERS is to be publicly or privately funded and, as national infrastructure, the Government will need to play a significant role. The nature of some of these project risks are now outlined and investors will need to be comfortable that a wide range of risks can be satisfactorily mitigated and managed.

H.2.1 Utilisation and Demand

As there are no historic data to support forecasting electric lorry usage, most of the work to predict utilisation is based on desktop studies. Several key events will occur to assist forecasting including future bans on sale of diesel HGVs. The uptake of ERS is still extremely dependent on the commercial benefits and incentives to lorry and fleet owners switching from diesel to electric. It is also possible that ERS may have competition from pure battery vehicles, or hydrogen or biofuel HGVs which add further complexity to forecasting. In summary, lack of data for a market which currently does not exist and hence certainty is not conducive to private financing. Amongst public sector investors, there is concern that there will be changing consumer patterns and that the market will determine that there are more efficient ways to transport freight than the 44 t lorry.

H.2.2 Technology

The technology required to deliver the ERS solution is currently available and relatively mature, but it is improving in incremental steps as significant attention continues to focus on innovation in the energy and transportation sectors. Examples can be seen in the HGVs themselves with vehicle autonomy and battery technologies. The catenary wire system, while only recently adapted for use in a limited number of trials on the highway, has been available for many years on rail and tramways. Related technology risks are considered manageable with due care and particular attention being paid when decisions on specific technologies being locked-in are made and for avoiding obsolescence. Currently it is understood that most of the equipment, expertise and technology needed will be readily available in the UK and the delivery is not dependent on long supply chains around the world including with such countries as China.

H.2.3 Revenue

A public or private solution may differ in the ways that revenues are recovered so the Government could simply apply a taxation mechanism and the private sector could collect on a user pays basis. An important element of revenue recovery should be that at no time would a vehicle be required to stop to make payment. Several technologies can facilitate revenue collection without intervention to a journey including the metering of energy consumption and number plate recognition with data forwarded to a payment system using sim cards for example. Controls over these collection systems can be set very tightly to avoid any revenue leakage including foreign vehicles registered outside of the UK. Taxation systems could recover revenues through a licensing system but some form of equitable mechanism relating to actual use should preferably be applied.

To set affordable tariffs in a private solution, utilisation of ERS is a critical component of the calculation. Too few users will mean higher tariffs or greater Government subsidy to ensure profitability, and this may also delay an increase in utilisation over time as diesel HGV owners are reluctant to switch to electric. Concern over utilisation will also deter private funders who will need to see a clear route to a return on investment if merchant risk prevails before an acceptable steady state of utilisation is achieved.

A complex situation will prevail in the early build-out days as the incentives for lorry owners to utilise the system will need to overcome their doubts about using an incomplete catenary system with insufficient static charging locations for HGVs. Range anxiety will be in the mind of every HGV driver and operator. To assist utilisation, the Government will be providing encouragement as the anticipated bans on the sale of new diesel-powered HGVs, weighing up to 26 t, in 2035 and the remaining heavier vehicles in 2040 increasingly take effect. This growth in utilisation over time up to achieving a steady state of operation is a component of the funding gap alongside the construction phase.

Another aspect of revenue collection which may need to be addressed is whether the Government decides to recover fuel taxes as the revenues from diesel, with fuel tax included, is replaced by electricity. Options are currently being considered for this and it is possible that a tax may be added to charges for the users of ERS through the tariff. Initial financing models indicate that at steady state there will be sufficient savings on current running costs to incentivise operators with a payback of 2 years. In addition, billing would include revenue to Treasury and to the operating organisation which should be sufficient to pay the financing costs and capital investment over a 20-year period. Alternative taxation mechanisms include recovery through a road fund licence, but this is not always seen as being proportional to usage of the highway and could be adjusted to a per mileage basis. If a tax is added to the tariff for HGVs, then care will be needed to avoid potential ERS users from charging their vehicles in other locations that could facilitate tax avoidance.

H.2.4 Demonstrator

One very useful component to de-risk the project is constructing and operating a 20 km (in two directions) demonstrator project on the M180 from Immingham towards Doncaster which will provide significant knowledge and experience. There will be an experienced cadre of people available to begin delivery on the rollout of the network going forward. This initial step,

by its very nature as a pilot with unknown outcomes, will need to be Government funded. Without an equivalent pilot scheme ERS cannot effectively proceed.

H.2.5 Grid Capacity

The shortcomings of the electricity grid across the UK and the need for significant and expensive reinforcement to support ERS could present a serious problem. Lack of available capacity within the grid is well known and locations suitable for new connections are reducing rapidly as capacity is being taken for many purposes including charging electric cars and vans. ERS will be competing for grid capacity or waiting for substantial reinforcement which could severely impede the rollout of the network across the UK. This will also be a problem to be overcome when selecting locations for the static charge points to serve HGVs.

Graeme Cooper of National Grid quotes the Sixth Carbon Budget when he predicts that the UK will need by 2050

- 2x energy consumption.
- 4x clean generation (renewables and nuclear).
- 2x grid capacity.

H.2.6 Delivery Cost Overruns

The specific delivery of the project will not be without difficulties, but electrification of the railways sets a precedent with continuous operations while non-electric rail services continued alongside. However, cost overruns were often a failing on the railway electrification projects and will raise significant concerns. Given the awareness of why and how these cost overruns occurred, delivery costs of ERS should have much greater certainty. An on-board battery on an HGV could facilitate the avoidance of expensive or high risk sections at bridges and interchanges as opposed to needing a continuous catenary system as with rail and tramways.

H.2.7 Disruption to Highways

Recent experience of the UK's smart motorway initiative rollout and the reaction of other road users to the disruption is a key risk to the ERS solution as other road users may react badly to what could be viewed as another smart motorway exercise. Avoiding disruption for highway users through various mitigation measures alongside public awareness campaigns could be critical in avoiding public intervention during the construction phases. Care will be needed to avoid any kind of protestor actions.

H.2.8 Uninsurable Risks

Financing risk through insurances is important for any project but uninsurable risks pose an unknowable or unacceptable risk of loss. These risks, which sometimes border on the occurrence of catastrophic events, need further consideration. Such events, both natural and otherwise, could be considered less significant for the delivery and operation of the ERS catenary system when compared with comparable cost infrastructure projects. Structural challenges of installing the catenary wire from an engineering perspective are not significant, as the assets and therefore potential defects are visible. The system itself, once installed, will comprise many sections independent of each other and an occurrence causing failure at one

location would likely not affect the operation of the network at other locations. Compare this with the Thames Tideway Tunnel, or a nuclear power station, where an event at one strategic location could take out the whole system. Government backing to cover these risks will be essential for ERS.

H.2.9 Scale

At an estimated cost of £20 billion, ERS is a significant piece of national infrastructure and should be examined for the opportunity to break it down into several component parts and more manageable pieces without affecting the whole and spreading financial risks across a wider group of investors. As an example to be considered further, connections to the grid are typically provided by the regional distribution network operators (DNO) and the catenary system will potentially need to be connected to the grid at multiple locations. However, grid connections and certain private wires can be owned, operated and maintained by independent distribution network operators (IDNOs) which own the assets through which the electricity is provided. IDNO's are allowed to use future revenues from their networks to help subsidise the initial costs of new network projects. This capital installation costs discount or asset adoption value can be very attractive and helps reduce the total capital cost of designing and building the power network. DNOs cannot discount in this way. The connections and private wires are operated in accordance with regulatory standards so there is no reduction in the quality of service from an IDNO. There may be a case to provide all connections to the catenary system through IDNOs who could help fund this piece of the required infrastructure.

UK Government grant funding opportunities should be sought, for example supporting grid reinforcement along the motorway routes. The rapid charging fund (RCF) is a £950 million fund to future-proof electrical capacity at motorway and major A road service areas to prepare the network for 100% zero emissions vehicle uptake. The need to support EV charging, particularly at motorway service stations where grid capacity is often inadequate, is critical to the Government's Net-Zero plans. The opportunity to work together should be seen as an advantageous proposition to the Government to maximise the benefits and utilisation of the fund if this can be worked into a solution for ERS.

A further opportunity could be sourcing energy from renewable generating assets; solar, wind and battery storage. These could reduce overall capital costs as well as reduce exposure to future price fluctuations in energy markets. Renewable energy generation being placed in areas where grid connectivity may be expensive and using battery storage to balance loading at locations of steep gradients or at peak demand time when energy is more expensive. All this supporting infrastructure could be funded privately and based on power purchase agreements (PPAs) with ERS owners and operators.

Opportunities to generate commercial revenues along the route which are not related to the tariffs for sale of energy and availability of the system should be considered to reduce overall financial exposure of the project. As examples, these could include various data management and information streaming services for autonomous or semi-autonomous vehicles.

As a further possible mechanism, regionalisation could break down the project into smaller and more acceptable funding packages. The National Highways network is regionalised with six regions, each having two sub-areas, and following a similar arrangement could allow funding packages to be reduced to levels which are seen as more comfortable for investors. It may also facilitate a model for rollout of delivery across the UK from several strategic

locations as well as catering to the possibility for competition. Benefits and synergies may also be gained with National Highways by following their regional boundaries. The six regions as shown below would likely create funding packages of £3 billion to £5 billion each.

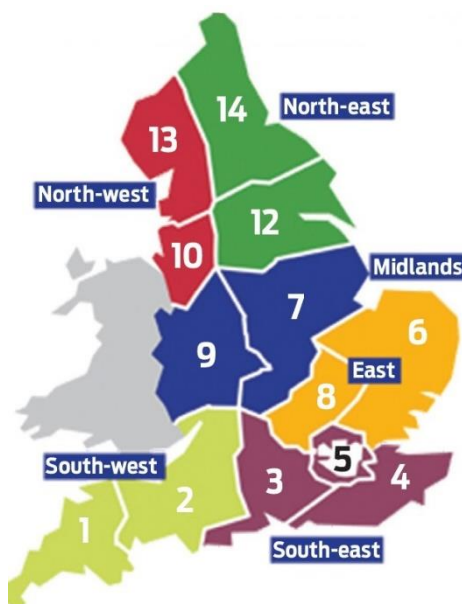


Figure H.3: National Highway regions (Source: constructionnews.co.uk).

H.3 Closing the Funding Gap

Critical to funding a private solution is filling the early funding gap to cover development, construction, operation and maintenance of ERS until revenues being generated from users will be sufficient to recover all costs including financing. At this point the project will become cash positive. It is initially anticipated that revenues will be generated through the sale of electricity per kWh and collection systems will recover both the cost of electricity and other fixed capital and operating costs. Revenues will increase over time as utilisation increases so there will be a need to ensure costs are covered until a sufficient steady state of revenues is reached. If a private sector funding and ownership solution is selected, then Government support will be essential in addressing the funding gap. There are several options including the allocation of a very small percentage levy on fuel duty and vehicle excise duty where revenues amounted to £37 billion pounds in 2019/20. An allocation over the early project years could be applied to support the early funding of ERS. If the Government agrees to fill the funding gap, then actual mechanisms will be a specific choice of the Government.

H.4 Tideway Example

There are several examples of national infrastructure of significant scale being funded privately. These models provide some guidance should ERS be privately funded. The Thames Tideway Model (Tideway) is increasingly being viewed as the preferred mechanism to use private funding and finance to support major infrastructure. Construction Enquirer recently commented on mechanisms to support Sizewell C as follows.

The Government said the switch to a Thames Tideway-type financing system, where some of the project's construction and operating risks is shouldered earlier on by consumers, will significantly lower the cost of capital by substantially increasing the pool of private investors like British pension funds, insurers and other institutional investors.

It claims consumers will save more than £30 billion from reduced financial risk costs over the lifetime of a new large-scale nuclear station like the planned Sizewell C.

The Nuclear Industry Association estimated it would add a small levy to bills of no more than a few pounds during the early phase of construction and less than £1 a month over the course of a project.

The changes in the Nuclear Energy (Financing) Bill will also end Britain's reliance on overseas developers for financing new nuclear projects.

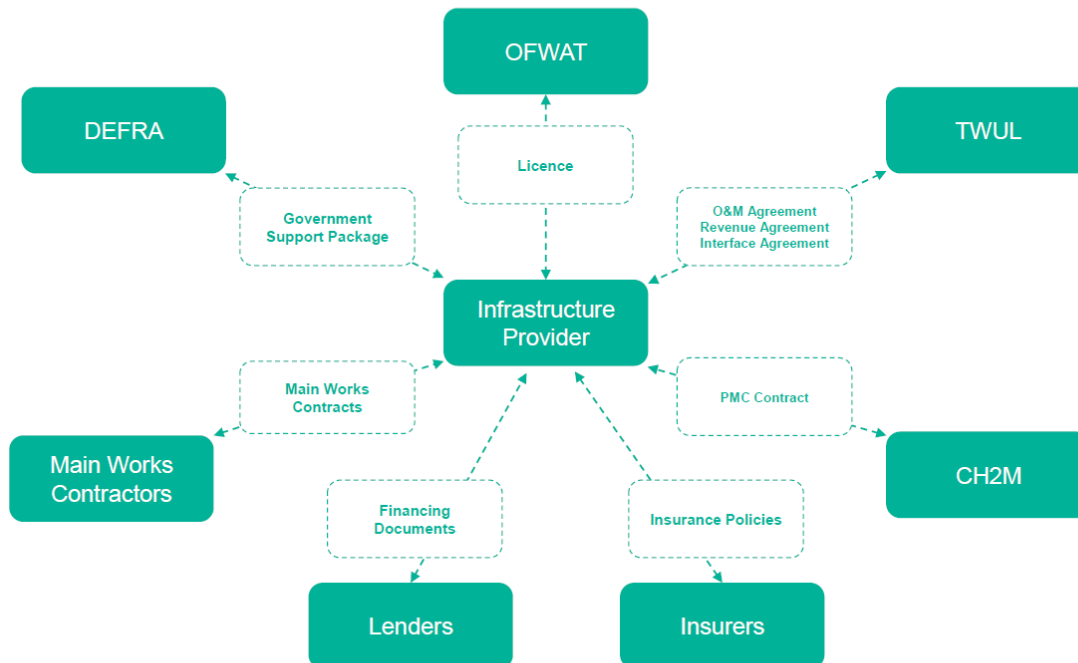
A key difference of the Tideway model, over other PFI schemes, is that it is accruing an income on Day 1 of the contract i.e. it is receiving monies throughout the construction period from a levy imposed on Thames Water users.'

Tideway has designed, is building and will commission and maintain the TTT which will have a 120-year design life. Apart from the technical differences, perhaps the biggest differentiator between the TTT and ERS is that TTT complements the privately owned assets of Thames Water and ERS complements the publicly owned assets managed by National Highways.

This difference is not viewed as creating any significant problems for a privately owned ERS positioned on public assets. Utility services are normally situated in conjunction with highways infrastructure where necessary legislation and Codes of Practice have been developed to allow effective management and operation of private utility infrastructure on public highways. A close working relationship between ERS owners, should it be privately owned, and National Highways can be defined. Given the proximity of the assets there will be significant overlap of services and it may be that National Highways provide certain types of services for ERS to avoid duplication, for example certain back-office services.

To assist in the consideration of ERS delivery structures it is worth taking a look in more detail at the Tideway to see how various parties have come together. The two diagrams below show the relationship between the stakeholders, shareholders and the infrastructure provider which in conventional PFI projects would be referred to as the Special Purpose Company (SPC). A critical player in the delivery of the TTT is Thames Water, which has successfully delivered significant infrastructure in six separate five-year multi-billion pound capital programmes over the past thirty years, so it has a proven delivery track record as a TTT partner.

Tideway delivery model



20

Figure H.4: The Tideway delivery model for privately funding major infrastructure projects (Source: www.tideway.london).

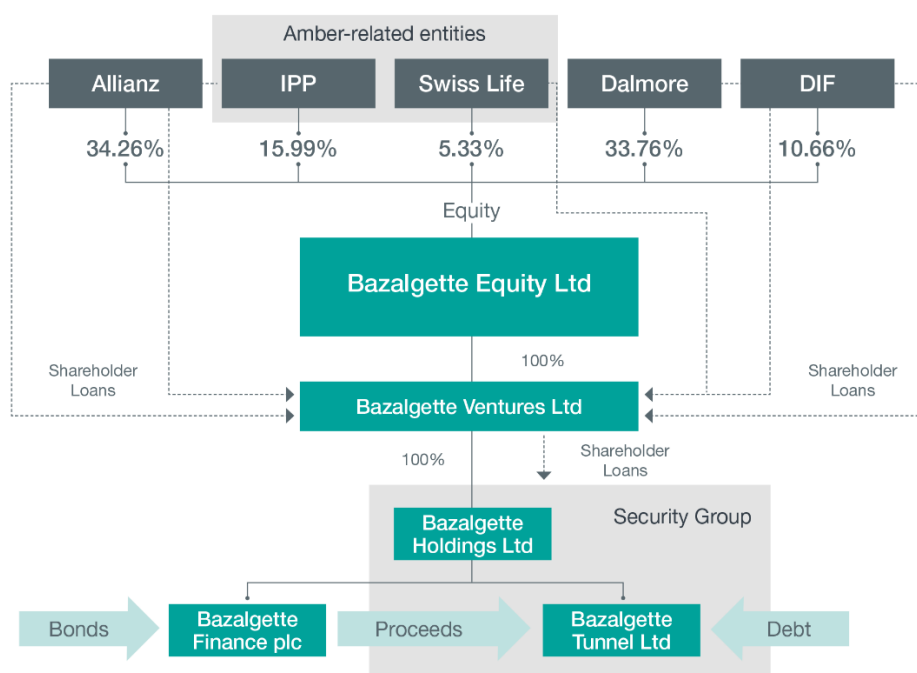


Figure H.5: The Tideway delivery model as applied to the licensed infrastructure provider Bazalgette Equity Ltd (Source: www.tideway.london).

Given the structures outlined above, a critical element is Government support even though the project is privately financed.

Government Support Package

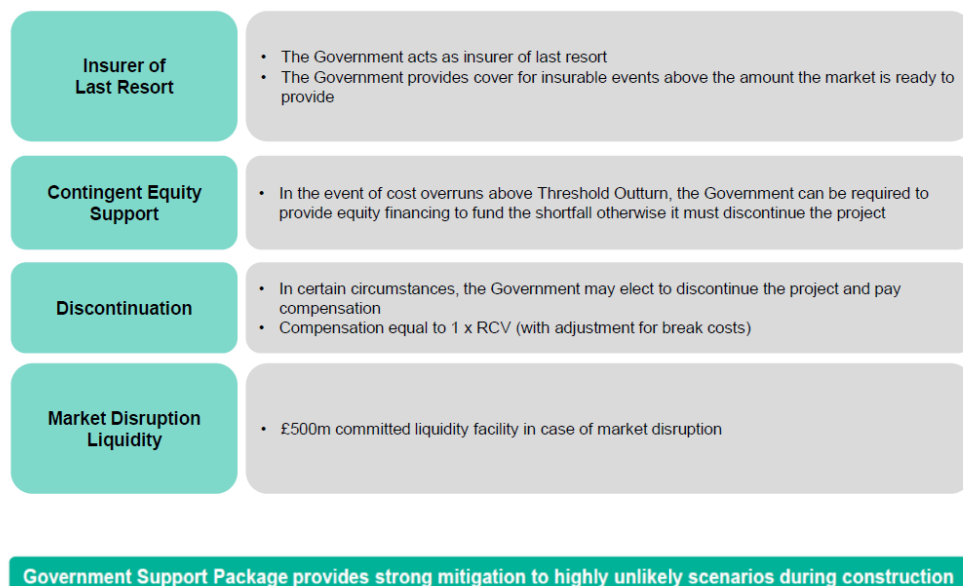


Figure H.6: The Tideway government support package (Source: www.tideway.london).

An equity first £1.3 billion investment from five shareholders, committed and backed by LCs, is funding the Tideway investment programme to the start of tunnelling. Debt is anticipated in the order of £2.6 billion and in place are a £1 billion revolving credit facility through six relationship banks and a fixed term loan of £0.7 billion with the European Investment Bank. Depending upon financial markets at the time, if a similar risk profile can be developed for ERS then an equity/debt split should be approximately the same or potentially better.

H.5 Conclusions

In a privately funded solution with appropriate risk mitigation measures in place, similar delivery and commercial models will be necessary for the delivery of ERS in order to encourage investors to participate. This would be attractive to the same types of investors that are involved in Tideway including major insurance companies and pension funds. Also, there is significant interest in capital markets for opportunities in pursuit of renewable energy, EV and EV charging solutions particularly if there is the potential for good ESG credentials. ERS is an ideal project in the decarbonisation of transportation sector and will meet the ESG and SDG criteria being set by many investors.

The proposed commercial arrangements and relationships for a privately funded ERS are set out below. Many questions regarding the ERS delivery vehicle will need to be asked and answered to move a privately funded project forward. Perhaps the most important question is who or what is the entity to deliver ERS. There is no private entity or consortium of private

entities that currently exist to deliver ERS or a project like ERS. This was the case with Tideway. Thames Water was already embarking on a project delivery plan for the tunnel and had a design and delivery team assembled but instead it conducted a competitive procurement process to select an independent infrastructure provider to finance, build and maintain the tunnel based on the lowest bid Weighted Average Cost of Capital, other commercial factors and deliverability. Bazalgette Tunnel Limited subsequently known as Tideway, was the successful bidder and was granted a project licence to design, construct, finance, test, commission, own and maintain the TTT by Ofwat. The Thames Water team was transferred across to the successful bidder. A similar procurement event could be envisioned for ERS perhaps with the demonstrator design and delivery team being reassigned.

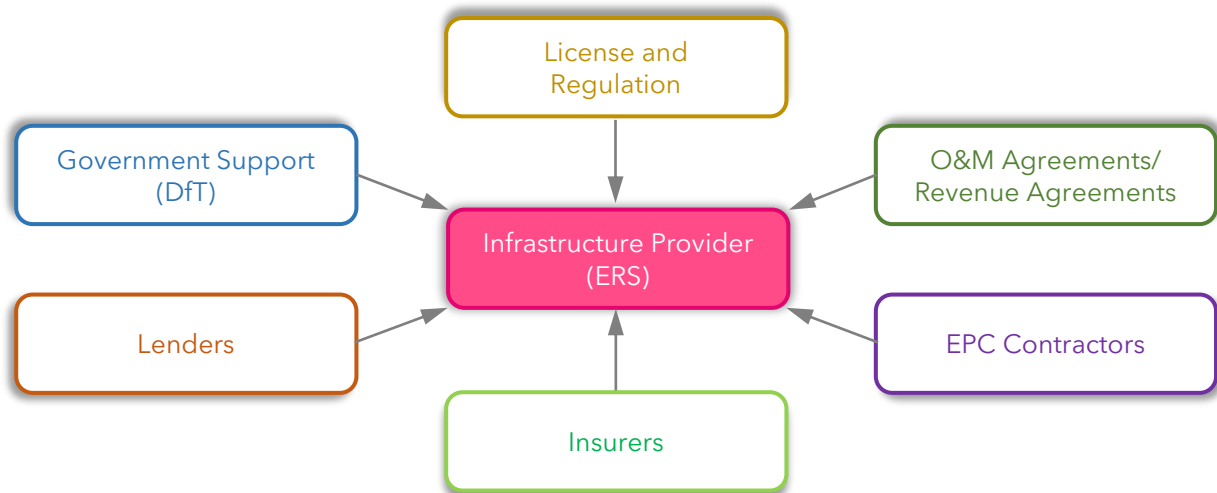


Figure H.7: The proposed financing structure for a privately funded ERS.

At this stage of development of the feasibility study, with limited knowledge of detail capital and operating costs and proposed tariffs, there are too many unknowns to determine whether ERS is financeable. However, with Government backing and the appropriate structures in place ERS has good potential to be privately funded.

In conclusion there are three options:

- 1 Public sector utility (most likely National Highways) to construct and operate ERS.
- 2 Regulated private sector utility, along the lines of TTT, with a Government backed insurance package.
- 3 Hybrid, for example DfT constructs the utility and runs it until 2040 when it privatises a fully operational and going concern.

As part of the Demonstrator Project's Proof of Concept element, these three options are evaluated.

Appendix I – Stakeholder Engagement

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Executive Summary

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- 9 – Local Residents
- 10 – Industry Bodies
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Section 2 – Further Analysis

Quantitative Analysis
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Section 3 – Conclusions & Recommendations

Conclusions
Recommendations
Acknowledgements

Executive Summary

Around 100 organisations have been contacted to understand their opinions. The meetings typically update and inform them of the current position of the feasibility study which leads first into questions of clarification and later into some opinions. The meeting concludes with a request for three areas of concern or subject areas to be developed.

The following themes with questions were pursued:

Planning

- o What is the demand for 44 t lorries in 2040 and beyond?
- o Will the consumer demands be the same in 2040 and beyond?
- o How does Freight Decarbonisation tie in with DfT's overall strategy and other government ones e.g. energy?
- o What will the policies and incentives be to encourage take up of ERS? (COP26)

Disruption

- o What disruption will there be during construction?
- o What disruption will be caused by HGVs running out of battery power?
- o What happens when there is planned maintenance to the inner lane?
- o What is the impact of ERS on SMART motorways?
- o What is the resilience of the system eg what happens if a length of motorway is closed longer than the battery range?

Haulage & Logistics Companies

- o What is the impact on operations?
- o Will we have to change operations to accommodate charging times?
- o Will we need more vehicles?
- o How does the transition period work?

Carbon

- o Does Freight Decarbonisation offer the best bang for the carbon buck?
- o What is the embodied carbon of the system?

Finance

- o How will it be financed?
- o What is the role of the private sector?
- o Who is paying for it (the user or the tax payer)?

Asset Ownership

- o Who owns the asset?
- o Who maintains it?

Safety

- o What happens if the overhead lines come down?

- o How is the system disconnected?

Power

- o What is the voltage?
- o What are the static charging options?
- o What is the impact on generation and transmission?
- o What is the range of a battery?

Roll Out Programme and Budget

- o How will the supply chain deliver such an ambitious programme as Great Western Railway?

National Highways represents the major stakeholder. Unlike other technologies, Electric Road Systems, using overhead lines, introduce a secondary asset to its highway network. Therefore, there are obvious concerns over ownership, safety and maintenance. The team has met it on a regular basis throughout the study and these points are developed in Section 1.1 of this appendix.

The Environment Agency sees Climate Change as needing immediate action and has adopted the mantra of “Adapt or Die”. Habitats will be a concern and this was trailed by Baroness Brown of Cambridge (Julia King) at COP26. Interestingly, visual impact did not feature very strongly until one of the last meetings. National Highways made a telling point that all motorway furniture and features are painted a specific brown colour between J28 and J29a on the M1 to meet the sensitivities of local tourist attractions.

COP26 gave a clear signal to the country and to the world that there was a swell of opinion and momentum to effect change and therefore meet the 2050 Net Zero targets. The themes coming from the consortium events and the logistics and haulage operators' workshop are the need for clear government policies and for incentives to encourage early adopters and for investment in the infrastructure.

Any proposed scheme involving new technology is dependent upon the “buy-in” of the operators. Their business models are based on the flexibility afforded by diesel. Many operate on a 24/7 basis and a single lorry undertakes a mix of journeys rather than a dedicated route or shuttle. Concerns were expressed about whole life costs and any potential reduction in payload caused by the weight of a battery.

Many of the above questions are beyond the scope of the feasibility study and therefore the Demonstrator Project will need a parallel project to develop “Proof of Concept”. The areas for further work will include:

- National traffic modelling
- Energy demand modelling
- Future consumer patterns
- Delivery of infrastructure
 - o supply chain capacity and capability
 - o ability to deliver on time and to budget
- Funding & financing modelling
- Transition options including hybrid HGVs
- Battery development modelling (including recycling)
- Business modelling of haulage and logistics companies
- Policy and Incentives to create change

Section 1 – Stakeholder reports

1. National Highways

	0 is no concern and 5 is hot topic	Comments
Early concerns		
Ownership of asset	4	Key issue – other technology solutions use the road network “as is” whereas ERS changes its nature. Who owns the overhead lines is still to be determined. Therefore, their maintenance and support have not been discussed in detail.
Safety	5	NH and Blue light services engaged with to produce the outline safety case
Risks	4	Risk register produced and still being developed which will inform the safety report
What have been the key topics for trial		
Disruption during construction	4	Topic has not been discussed yet. M180 being a 2 lane motorway could be a hot topic
Standards	3	Topic has not been discussed yet.
Height of OLE	3	Height in general has not been a major concern. Finding a solution for low bridges is a major one.
Bridges	5	A number of bridges will require rework to provide the required clearance.
Impact to OLE support	3	Currently not clear who would own the asset and as such maintenance and support have not been discussed in detail.
Maintenance of OLE	3	Currently not clear who would own the asset and as such maintenance and support have not been discussed in detail.
Accidents	4	Important due to safety implications. Also, electric lorries are something new. Vehicle modes of failure will need to be understood and how to be dealt with (i.e. how to remove a failed vehicle, is there a mode of failure that would result in vehicle wheels to be locked).
Incidents caused by OLE failure	4	Safety is important.
Interoperability	2	Assume interoperability with Europe. Not raised as an issue
Battery capability on off network trial	4	Battery capacity and vehicle range off network is important. Better planning required, careful positioning of static chargers
Capacity of trial to test congested conditions	4	Been modelled by Siemens
Blue light services	4	Engaged and included within the safety case output
What topics have been broached concerning the eventual/possible roll out		
Charging times	0	Included within the static charging report and the WP4 demonstrator strategy for different types or vehicle movements
Static charging network	2	A proposal for the demonstrator is defined. There is also a national roll out methodology and strategy outlined with costs

SMART motorway integration	2	Under review, will be available end of Jan 2022
Future areas of discussion		
German visit	4	From the meeting on 08/12/21 this is still under discussion and maybe hindered by COVID etc
Sub Demonstrator @ Moreton (CEO is Clair Mowbray whom I have met)	2	This has been agreed in principle by Moreton in Marsh but from the angle that it would provide a live training facility for operators, network maintainers and emergency services. It may also be useful from a buildability perspective on training the construction teams

Table H.1: National Highways stakeholder report

2. Operators

2.1 Overview

Statistically in 2020 15,212 million t.km of goods by rail¹ compared to 144,209 million t.km by road². There are 109k HGVs over 33T and 34,000 road haulage companies trading in the UK³. This helps put into context the relative importance of road. 89% of all freight and 98% of food is transported by road. ⁴

The logistics and haulage sector is a broad one with large fleets at one end and owner operators at the other. The industry is said to have a long tail and, in this respect, can be likened to the construction industry. At the smaller end, these are often family businesses which have evolved to reflect a changing market. A three generation company will typically have started in agriculture, moving to primary industries e.g. mining and now operating a more flexible approach. For them, day to day operations are more of a priority than climate change.

On the other hand, transport is often part of a larger commercial operation e.g. John Lewis. For this end different considerations come into play. Public perception, investor sentiment and shareholder preferences are a key part of their thinking. At COP26, the expression “money has a conscience” was evident. For these higher end companies, climate change and a green agenda are key considerations. Senior managers appealed for mechanisms to justify green recommendations and feed their Boards with a compelling argument.

UK haulage companies may, therefore, be crudely divided into a 20:60:20 split. 20% are early adopters and willing to embrace change. 60% are cautious and wish to observe trends before committing to new ideas. The remaining 20% remain sceptical of change. This very much applies to a company’s approach to climate change. ⁵

Diesel powered lorries are the status quo. Business models have been established around the flexibility of refuelling, reliability, maintenance regimes and the residual value of vehicles. At the smaller end, companies anticipate hydrogen as being the natural answer to their current position. It is perceived as a like for like substitute.

ERS is a much bigger step. For the “enlightened” 20% then the transition period is of concern and some have also been attracted to biomethane which might provide a green range extender for the hybrid vehicle.

¹ [Rail freight transported: UK 2006-2020 | Statista](#)

² [Road freight transported in the UK 2006-2020 | Statista](#)

³ [Fun Logistics Facts & Stats | HGV Alliance UK Ltd](#)

⁴ [Road Haulage Facts and Stats \(rha.uk.net\)](#)

⁵ Interview with David Wells – 9 Nov 21 at COP26

The Government has announced that there will be no new diesel HGV sales after 2040. Typically, companies retain their vehicles for 5-8 years and therefore companies will not be obliged to buy non diesel vehicles for another 4 cycles. For the family owned businesses, this will be the concern of the next generation.

Emerging from the Operators Workshop (see below) is the use of lorries by the fleet operators. Nestle for example have 15 lorries which operate 24/7. At the KTN Big Battery event on 14 February 22, Howard Tennens provided a similar picture with limited break times for drivers as their travel times are carefully planned to maximise the use of the lorry. This is created by pre-loading trailers at factories and warehouses, thus allowing lorries to turnaround quickly.

The objective of the ERS strategy is to not to impact adversely on the operations of a haulage company. Therefore, locations for static charging becomes a key point. Drivers already suffer from poor facilities and there is doubt whether warehouses and hubs will provide charging points. There is ongoing concern on how to service more remote areas. High utilisation rates have brought into question whether more vehicles will be required.

In the news recently is the pushback of housebuilders who do not wish to have to carry the cost exclusively of providing EV charging points. Likewise, operators are concerned that they will have to carry the cost of the £20embodied network infrastructure and a further sum for the upgrade to the transmission network.

Motorways need to close for planned maintenance often at night and more worryingly, they are closed due to accidents and reactive maintenance. It is unclear what contingencies there are for the suspension of stretches of the overhead lines which exceed the range of the battery.

2.2 Operators' Workshop on 26 January 22

14 Operators were represented at the workshop with further representation from industry bodies (SMMT, Logistics UK, Retail Forum and Road Haulage Association). In addition, DfT was present.

2.2.1 General

The operators represented were largely blue chip, They are influenced by customers and investors, and are keen to adopt a green agenda. They echoed some of the comments that were aired at the Scania Conference on 8 November 21. They need clear policies from the Government and a reliable infrastructure from the ERS programme.

Reliability is sought on energy supply, billing mechanisms, vehicle performance and support, costs and maintenance of the system. A clear programme is also being sought.

2.2.2 Vehicles

Diesel offers a huge amount of flexibility and this is needed in the design of ERS lorries. This led to the need to drive for 200 km off the grid without "refuelling". This line of argument leads to a greater use of hybrids and range extenders.

Not reducing the existing the 44 t weight limit with a heavy battery is critical to most businesses and therefore, maintaining payload is a priority. Coupled with this is the desire to maintain the size of the existing fleet. In other words, operators do not want to have to increase the number of vehicles to embrace the new technology. This could occur because the payload is reduced to accommodate a battery or due to protracted journeys to maximise the use of the grid.

There was a general understanding that vehicles may have more dedicated routes that follow the grid rather than the existing mix. It was also accepted that there would not be retrofitting of current diesel vehicles with batteries and pantographs.

There was a general concern that new proposed loadings did not affect axle loading.

Operators are looking for an automatic pantograph. This is one that senses the overhead lines and retracts when leaving the network or overtaking. They are concerned that any extra equipment should not impair safety and awareness of vulnerable road users.

Battery performance and its potential range were major considerations along with training. Training covers drivers, maintenance teams and recovery units. Maintenance training should extend to the dealerships.

2.2.3 Costs

There is a general concern on who will pay for the infrastructure which includes static charging points. The latter includes 3rd party providers and those housed at warehouses and logistics hubs. Operators believe that these should be installed with the support of government funding.

There is also the total cost of ownership which should not be greater than the diesel equivalent. A three year cycle was given.

Billing for use of the energy needs to be transparent. There was a query on whether operators would be compensated if the system is unavailable. (This might become a wider concern following Storm Eunice on 18 February 22.)

Government policy remains unclear as the concept is still in its infancy, but operators wanted to know more about incentives and potential tax regimes. Transition period was identified as a tricky time for operators who would also like to use biofuels as a range extender. They wanted an incentive for embracing a costly but green solution.

2.2.4 Infrastructure

Much of the challenges and needs were centred around reliability. Minimising disruption is essential, and this includes the maintenance of the system. Static chargers will be available off the network but there needs to be a mechanism for booking slots and avoiding excessive queuing. The cost of using static chargers needs to be transparent.

Interestingly, they were interested in supply and local renewable sourcing of energy. Allied to this was battery storage but this concern is linked to reliability. Power supply should not limit the number of vehicles on the system.

As we move into the potential of 5G, then it will be possible to track all vehicles on the system and to forecast travel times accurately.

Interoperability was a major issue, and any UK system needs to be compatible with Europe.

2.2.5 Other Considerations

Driver welfare is of particular concern for operators and is damaging their ability to recruit. In addition, it is compromising their ability to implement a more diverse strategy. Therefore, any improvements to the network needs to be accompanied by an upgrade to driver facilities.

Future technologies will allow the take up of automated vehicles.

3. Central Government

COP26 has helped to concentrate the minds and there is a general focus and momentum to finding solutions for climate change. Climate Change challenges all departments and finding a transport solution is an issue not only for DfT but also BEIS (energy) and Treasury (funding and finance).

For many in Government circles, the easy decisions have been made and now there is the need to take on the harder ones. These tend to have longer time scales that look beyond the immediate political 5 year cycle. They include climate change, positioning the UK in a post Brexit economy and construction productivity.

For the public sector there is a high level of accountability and therefore there is a concern that any transport solution has the resilience to be the right one in 2040 and be viable for a

further 20 years. This line of thinking questions future demand, travel patterns and transport modes.

On the other hand, it is human nature to worry about risks that are beyond one's immediate control. Therefore, DfT is comfortable that it has a coherent vision reinforced by projections for demand. In its opinion, there is unlikely to be a switch to smaller more flexible vehicles and there is insufficient capacity on rail to contemplate a major modal shift.

DfT's "Decarbonising Carbon" outlines the need to prioritise HGVs. Transport at 27% is the highest sector contributor to GHGs, of which HGVs account for 16%. However, for some the infrastructure network price tag of £20embodied needs greater justification on whether this will deliver value for money in terms of carbon bang for the buck. Therefore, in their eyes better value might be derived by prioritising certain industries e.g. cement and steel.

Electric Road Systems (using overhead lines) represents a proven system. There remain sceptics on whether industry has the wherewithal to deliver an ambitious roll out programme to time and budget. Great Western Rail is quoted regularly and the disappointment of cost escalation resulting in electrification plans being partly abandoned.

DfT will need to reassure fellow Government advisers that future major infrastructure projects will not spiral like HS2. In Section 2.2 of this appendix, lessons from 2018 NAO report (Investigation into the Department for Transport's decision to cancel three rail electrification projects) and subsequent rail electrification projects are considered.

There is undoubtedly strong support for hydrogen in certain circles as a sweeping solution. There is the lateral thinking that hydrogen can be produced on a vast scale using PV sources overseas and shipped to the UK. However more mainstream is that it will have a role in some capacity e.g. marine and industry clusters.

All systems will need to consider embodied carbon to ensure universal acceptance.

There is growing support for a blend of technologies which will allow for HGV services to extend beyond the network and therefore reach out into more remote areas. As the research has progressed, there has been further interest into rapid charging solutions.

There is general interest in the role of the private sector and how this might support the financing of such a project. A good starting point is the Thames Tideway as a model. Posed but unanswered in the discussions is the role of Government. In Section 8 of the main report, various models are considered.

Undoubtedly, there is interest of how an ERS arrangement will be integrated into the SMART road system which has gantries, variable speed control and hard shoulder running. This is in addition to various technical questions which are considered throughout this report.

4. Environment

Environment Agency hold strong views and follow chairman, Emma Howard-Boyd's appeal "to adapt or die". ERS is a technology ready solution and every year that a decision is delayed then the risks of flooding, rising sea levels and water shortages increase. It is time for some difficult decisions to be made in order to save lives.

Local engagement is part of WP5 and identifying the consents required to deliver a demonstrator project on J2 to J5 of the M180. In Section 2 of this appendix, this is detailed along with a series of local workshops to identify specific environmental concerns and to investigate opportunities to improve social value

In summary the environmental team, has conducted a desktop study using GIS survey data to make a preliminary assessment of any potential environmental risks that would likely arise from the ERS development. The study has been conducted in a spatial manner through interrogation of survey databases for data environmental constraints near to the M180 motorway.

The aim at this stage has been to inform the consenting process by establishing (or at least predicting with a reasonable degree of certainty) whether the ERS development will cause “significant environmental effects”. This preliminary environmental assessment (available in full form in the WP5 section) considers areas of environmental constraint including listed buildings, parks, conservation areas, wetlands, woodlands, areas of outstanding natural beauty, air quality management areas, flood zones and water sources. The study shows that these areas are either situated at sufficient distance from the M180 as to not be affected, or that they are nearby (i.e. within 1 km) but are not likely to be affected because the ERS will require minimal land take (i.e. no/minimal land affected outside the current motorway boundary). There is a nearby area of air quality management which is likely to be positively affected by the ERS development, i.e. from a reduction in HGV exhaust emissions on the M180.

The study has established with reasonable confidence that the ERS development will not cause significant environmental effects, and therefore a full EIA will not be required on this basis.

Baroness Brown of Cambridge (Julia King) identified potential concerns when she said that she was interested in the habitats that frequent the verges of roads. A Wildlife Trust report on HS2 highlighted 693 classified wildlife sites within 500m of the M180 route.

In the main, most groups accept the need to address the problem of greenhouse gas emission from HGVs and therefore they are committed to a green agenda. Many believe that a “modal shift” to rail is the answer. This preference, though, ignores that this would require more rail lines as the current system is nearing capacity with freight and passengers sharing the same line.

Some strategists challenge the causes and prefer to operate with a clean sheet of paper. Therefore, the need for freight movement and a more radical view are put forward rather than just finding a diesel replacement option.

Visual impact is a discussion point and as various user groups have identified might also impair the appreciation of the countryside by road users depending on the frequency of the support pylons. There has been work done in the rail sector to reduce the impact and “to sit more harmoniously within their environment.”¹ Interestingly in Section 2 of this report, local people do not see visual impact as an issue for roads. However, in one of the last interviews National Highways indicated that all motorway furniture between J28 and J29a on the M1 has been painted a specific brown to accommodate the sensitivities of heritage and tourist sites.



Figure H.8: Brown-painted motorway furniture

In the roll out of the electric road system, increasing concern is anticipated around the connections from National Grid to the ERS network. The Campaign for National Parks has rejoiced in a recent independent study that identified twelve sections of high voltage lines in

four National Parks and a number of Areas of Outstanding Natural Beauty which have been shortlisted as having the most significant landscape and visual impact⁶.

The issue of birds and overhead lines is a concern of the RSPB . Environmental groups have identified that most electric lines are built around the average bird flight level, but are hard for birds to see. Raptors are especially at risk because of their large wing span. Not only do power line collisions and electrocutions cause bird deaths, but they can also cause power outages. They can also cause harm when they cut across an important migratory pathway or stopover site.⁷

In Section 7 and Appendix A, there are discussions around embodied carbon and a comparison between ERS and other systems under consideration. This issue was also of importance to Ros Jones, the elected mayor of Doncaster.

A weakness in the current ERS and big battery arguments is the inability to cost effectively recycle lithium ion batteries. It is currently cheaper to build new than to recycle. Other issues include difficulties of recycling the key materials and they include dangerous toxins and therefore are not good landfill.

Non environmental groups have asked about the cost of decommissioning the system and internally the team has discussed a lorry scrappage scheme to encourage the transfer to electric before 2040.

5. Local Government

A characteristic of Local Government in the area is the steadfast support of a green agenda. In a “A Green Future: Our Plan For Positive Change”, North Lincolnshire Council has committed to being net zero by 2030. Doncaster Mayor, Ros Jones, and local MP, Ed Miliband, have combined to create a plan for the local area.

Therefore ERS, a green initiative, is viewed positively at local level. The area is alive with renewable energy projects. The local players express a neutral approach but emphasise their current involvement with other initiatives. With the immediate region being dominated by ports, then there has been an emphasis on hydrogen as the larger businesses are petro-chemical e.g. Philips 66.

In a meeting with elected Mayor of Doncaster, Ros Jones, it was emphasised that at this stage, politicians will adopt a technology neutral position. Committed to a green agenda, they wish to see a balanced argument and compare technologies in terms of carbon impact and economics.

The area is identifying with the renewable energy industry. Dogger Bank will be the largest UK offshore wind development. Siemens has built a large turbine manufacturing plant in Hull. Greater Lincolnshire LEP states “Green energy has been identified by the Greater Lincolnshire LEP as a 'game-changer' sector offering unprecedented opportunities for future projects, growth, expansion, and investment over the coming years.”

With green plans in place, LAs are keen to understand the timescales. At the more optimistic end ERS hopes to be in place with its demonstrator to run from 2024 to 2026. M180 is the pilot for the rest of the country and so, LAs accept that it is an Inward Investment opportunity. They also see it tying in with local education provisions e.g. Boston College which has just opened a new Engineering and Manufacturing Technologies building and a Digital Transport and Logistics Academy. Doncaster is home to the National College for Advanced Transport & Infrastructure.

⁶ [Plans to reduce the visual impact of overhead lines welcomed | Campaign for National Parks \(cnp.org.uk\)](https://www.cnp.org.uk/campaigns/overhead-lines/)

⁷ [Dangers Of Migration for Migratory Birds - The RSPB](https://www.rspb.org.uk/birds-and-wildlife/bird-care/bird-protection/migratory-birds/dangers-of-migration-for-migratory-birds/)

There was interest in how new electric HGVs are to be maintained and serviced. This could lead to new opportunities for FE Colleges.

Doncaster has a history of heavy engineering and is opening a series of new business parks. Scunthorpe is closely associated with steel. There is further opportunity to link up with Immingham's Freeport status which was confirmed in March 2021 and emphasised by the LEP.

On the negative side, the LEP expressed a concern of how this new infrastructure was going to be paid for and how that might impact on businesses in the area. Many of Transport for the North's comments are more aligned with those for Central Government. However, it is worth noting its difficulty to gain planning permission and consequently its doubts over whether a full roll out by 2040 is possible. Interoperability (with Europe) is a concern.

There are issues with transport services linking Immingham to Doncaster. The LEP was keen to trial a coach service to alleviate this issue and to look at green transport for the area.

In the North Lincs meeting, we discussed the attractiveness of the area to new businesses. It boasts of good connectivity to the major transport arteries and this is reinforced by its proximity to ports. The expansion of the Freeport and land generally offer space to develop. There appears to be funding available to support new businesses to the area and there is available energy.

In a separate exercise, the team has looked at whether it is possible to create a ribbon of excellence along the M180 combining Doncaster, British Steel and the Freeport of Immingham. British Steel at Scunthorpe was shortlisted by Heathrow for its Regional Hub programme. The challenge is to reproduce this concept to service the construction, ERS, offshore wind and possibly manufacturing industries.

The region has the right skills and educational infrastructure to support such a development.

6. Local Businesses

Doncaster is positioning itself as a "Logistics Gateway". There are major developments at iPort, Armthorpe and a 350 acre regeneration site called Unity. Therefore, to have a progressive scheme feeding into the hubs is seen as a benefit.

British Steel is based in Scunthorpe and employs 4,500 people. From a transport perspective, they saw it as an opportunity. Most of their bulk requirements arrive by rail. However, they run a shuttle service to and from Immingham and they would be interested in using the demonstrator. The benefit to British Steel would be to be seen to be embracing environmentally friendly solutions.

Jingye Group acquired British Steel Limited in 2020. The new owners have a different approach to transport and this could be to the advantage of the Demonstrator Project. Currently British Steel uses logistics platforms to contract out its transport requirements. Empty returning lorries to Immingham pick up loads from Scunthorpe.

There were concerns about work on the M180 between J4 and J5 as there is no easy designated detour. If installing a 2T battery to the tractor leads to a payload reduction of 2T then this will result in an 8% extra cost.

In general, local businesses are interested in ERS. Individuals recognise the importance of climate change, however are reluctant to make the initial move if it has a cost implication. Therefore they are fairly neutral about such an initiative.

There has been some concern expressed in other circles that there would be a concern about the visual impact. This was not seen as an issue.

Local businesses are used to the M180 being disrupted, it currently has road works between J2 and J3 and there is no exit at J2. For many, the short term inconvenience is compensated by the long term benefits.

Some SMEs thought there might be a direct benefit from the demonstrator project but more were more neutral although they could see the benefit to the local area.

A 6,000 acre farmer adjacent to J2 on the M180, also generates his own power from renewable sources. He saw the demonstrator as an opportunity. As a consequence of this discussion, the consortium is looking at harnessing local renewable power for the system and also using local renewable power for the potential construction compound and laydown area.

7. Emergency Services

Similar to LAs, the emergency services are very supportive of climate change measures. This is despite being averse to change. However, savings have ensured that they have had to remain flexible of mind. Ambulance paramedics nowadays take the available vehicle rather than operating a dedicated one. Often vehicles can do 500,000 miles over a life time.

It is worth noting that the A&E facilities local to the M180 are Scunthorpe, Doncaster, Grimsby and Hull. There are also specialist trauma centres at Sheffield and Nottingham.

The police are often first on the scene and therefore tend to direct the other services unless the incident is a major one and requires a more specialist lead. On some occasions extra resource may come from outside the area but they operate under the direction of the home team.

The overhead lines may present a problem for the air ambulance.

As discussed with the HGV recovery teams, road fatalities require investigation and sometimes road closure. The police said that 42 occurred in the previous year. Most of these were on rural roads and caused by an underlying medical condition.

Services are concerned about being prepared for various scenarios. They would like to have the appropriate training and the reassurance that their personnel will be safe. Consequently, they are keen to establish a process for isolating live overhead lines which are perceived as a major danger.

Experience with electric cars, has led the Fire Service to be cautious with battery fires. The current system is to douse them with water but there may be better solutions including equipping fire engines with a new mechanism.

As a side note, interestingly, the intensity of traffic on the M180 is linked to the tides as vehicles embark and disembark at the Port of Immingham. In the event of a blocked road there are diversion routes. The police pointed out that the village of Ulceby has been quite vocal in the past on this subject. (See Section 1.8 of this appendix)

Naturally, a concern was around the likely disruption caused by construction and whether there will be lane closures, reduced lane widths or minimal disruption allowed for by night time working.

All the services were concerned with various scenarios – chemical spills, impact on pylons, fires to electric HGVs, overhead lines coming down and vandalism. In addition, there is the issue of protestor action and how this might be managed during construction and then operation. In addition, the transport of abnormal loads is an area of concern.

Interoperability is a consideration and the need to have a system which EU lorries will be able to use.

The police identified a series of questions which were largely supported by the Fire Service. This has been the basis of some detailed work in WP5.

Another interesting aside was raised. In the event that the demonstrator proceeds but the national roll out does not, who is responsible for the decommissioning of the M180 works? Another was whether air quality is due to be monitored.

8. Local Residents

Parish Councils are concerned with the safety of their community and improving the environment and facilities available to them. Therefore, of particular concern is traffic and ensuring that it abides by the speed limits and that villages are not inundated by HGVs.

HGV traffic leads to noise, pollution, safety concerns and damage to the roads. In addition, people buy houses in villages and do not wish to have their investment threatened by unwanted HGVs or developments.

Some communities (e.g. Ulceby) are concerned by a rising use of their village roads as “rat runs”. Others (e.g. Scawby) have no immediate pressing issues but are worried by the prospect of official or unofficial detours, due to road closures, coming through their village.

Non affected residents are not concerned by the visual impact and think that the original act of building a road is unsightly. None of the residents were particularly concerned with the disruption to the road per se. Their concern was more the consequences of the disruption. They tend to see a benefit arising from the reduction in local pollution and possibly the noise. The M180 can be heard in some of the nearby villages.

Reassurance will be required that household electricity supplies will not be affected by what is perceived as a major additional demand or as a consequence of an incident on the M180.

The village of Ulceby had some more specific issues. These are based on its proximity to Immingham Port and their continual issues with the A180. The A180 runs from J5 of the M180 to Immingham Port and beyond. It is in parts a concrete surfaced road and was built in 1985. It is two lanes with no hard shoulder and has regular laybys which allows HGV drivers a break. The road requires regular (reactive) maintenance. There have been several accidents caused by drivers leaving laybys and being unaware of approaching traffic.

Immingham Port is claimed to be the busiest port by tonnage in England. It has undergone several recent developments with more in the pipeline resulting from Immingham being granted Freeport status. Sat Nav routes and using the local airport by the port for storage have increased the through traffic in Ulceby.

Residents are worried that work to the M180 and the trial itself will lead to more vehicles passing through the village. The area also suffers from severe weather conditions during the winter and there is a question over how the system will cope in these circumstances.

Interestingly Parish Councils can contain a local councillor and their political concern is embodied carbon and how ERS compares in terms of carbon footprint to other technologies. This comment was also aired by Ros Jones of Doncaster.

9. Industry Bodies

Industry bodies have been broadly supportive whilst professing being technology agnostic. They recognise the urgency associated with Climate Change and are drawing up their proposals to meet it.

The three groups represent transport planning (ICE, IET and CIHT), logistics (CILT, RHA and Logistics UK) and lorry manufacturers (SMMT). Interestingly although their issues and interests were similar, they were approaching it from different starting points.

All three were interested in the cost of the roll out. The engineers were concerned about the overall affordability whereas the logistics and manufacturers were more concerned about the contribution that they would need to make, in other words whether this large investment was going to impact adversely on their businesses.

The construction phase was of interest. On the one hand it was the disruption that was likely to occur – a potential impediment to road users including lorries. On the other it was whether

the programme was achievable. There was also a question over how it might interface with the SMART Motorway Programme.

Some engineers like an empirical approach and this leads them to a starting point outside the considerations of lorry manufacturers and operators. These people question the current mechanisms to move freight and use the opportunity to test their own alternatives e.g. shipping. (This view was also aired by some environmental interests and was along the lines - "if I was starting this journey, I would not be starting from here.") More generally they tout a modal shift argument.

Flexibility and functionality are key to logistics businesses and these are afforded by diesel. There is a nervousness around platooning and autonomous vehicles because these might be too restrictive to the logistics industry. For some operations the lorries run 24/7.

Planners are interested on how the network will operate and how the static chargers will dovetail into the system. Logistic bodies are more interested in the exposure to shortages of power. The manufacturers are interested in the battery size and the range it provides. More range leads to a heavier battery and therefore payload sacrifices.

There is a general uneasiness of how the future will unfold. Therefore, manufacturers and operators become nervous around future demand. Those on the planning side who have been involved in major projects join this chorus. Those on other carbon initiatives, question whether it will give the anticipated carbon return. Others question DfT's Decarbonisation Plan as being too aspirational.

10. Energy

Graeme Cooper (National Grid) quotes regularly the Climate Change Commission report which states that compared to today in 2050 there will be:

- 2 x energy consumption
- 4 x clean energy generation (renewables and nuclear)
- 2 x grid capacity

Paradoxically, the peak demand for power in the last 20 Years was in 2002. The 62GW required then contrasts with 30GW that was needed in lockdown.

All the new technologies will draw on this expanded infrastructure. Interestingly, although it is a concern of those outside this bubble, it does not trouble those inside. Offshore wind generation appears to be in hand with around 40GW in the pipeline. There is a confidence that increased capacity is available and is subject to a commercial arrangement.

In addition, BEIS appears to be confident in importing "green" hydrogen from overseas solar farms if necessary. There is a sense that this would be commercially viable. BEIS itself has invested emotional capital in hydrogen. Although it is neutral, it will need ERS to prove that it represents value for money both financially and in terms of carbon reduction.

New connections require long lead in times with National Grid but the grid largely follows the strategic road network so is complementary in terms of location. Therefore, connections should be relatively easy to make. Both National Grid and Northern Powergrid encourage early involvement which allows them to explore the optimum solution.

The £20embodied estimated as the cost to roll out the network will include the overhead lines, the third party static charging points and the associated connections. (Due to relatively low energy requirements, Northern Powergrid has been sounded out to support the M180 trial.)

There is general interest in who will own the overhead lines. The conclusion of the finance report is that it will either be owned by a regulated utility or a public sector organisation. For Northern Powergrid to step in as an investor, its investment arm will need to be reassured that

there is a long term demand for ERS. All parties are keen to see that there is a general appetite and therefore uptake by the operators.

There appeared to be little concern about the technology required to monitor use of the power and then to subsequently charge for it.

Mechanisms to store energy become an area of interest. National Grid report that offshore wind is looking at hydrolysis as a mechanism to store energy in the form of hydrogen. Northern Powergrid were interested in batteries as a way of ensuring that the supply is steady. In addition, batteries could be used to aggregate local renewable energy. SSE continues to oversee pumped storage schemes in Scotland.

Northern Powergrid and others were keen to explore extreme scenarios to understand fully the peaks and troughs. All believed in a coordinated approach.

11. Others

The findings from the financial community, in essence, do not differ from the public sector. If anything, they are more risk averse. The roll out scheme which will theoretically start in 2028 is too far ahead to be considered as funds are looking for returns inside 5 years.

However, in the main funds are seeking low risk projects. This means there needs to be certainty or guarantees around level of demand and uptake as well as costs. If The Tideway Tunnel model is to be used, there would need to be an income stream during construction. This would be afforded by government.

SSE, Orsted and Phillips 66 have been approached. They have either declined to meet or not responded.

12. Media and social media engagement

An important part of our engagement approach has been to use key moments to educate the general public about our feasibility study. This has focused on explaining why decarbonising road freight is so important to the UK, going into detail about the project, what it entails and its benefits.

We have released two proactive press releases since July 2021:

16 August 2021: [Green light for path to UK's first 'electric motorway'](#) and

10 November 2021: [Removing carbon-emitting HGVs by 2040 welcomed by Costain](#)

In addition, we created a [LinkedIn page](#), where we have promoted content that explains the programme, including a five minute film and covering our attendance at two events during COP26 in November 2021.

Media coverage

We have benefited from a range of media opportunities from national print through to local broadcast. From a national media perspective, we have featured in the Guardian, the Times, the Sunday Times and the Telegraph,

Social media

We set up a LinkedIn page in November 2021 to enable us to share content, specifically while we took part in Scania's EuroCentral launch event during COP26 in the same month.

To date, the page has 309 followers (21 February 2022) with posts achieving good levels of engagement.

Section 2: Quantitative Analysis

1. Introduction

Two surveys have been conducted.

- Operators Workshop on 24 January 22
- Doncaster & North Lincolnshire Businesses on 3/4 February 22

Further surveys were planned at Roadshow events but these had to be shelved due to the concerns of the Covid-19 Omicron variant.

These surveys have been supplemented with Desk Top Analysis.

2. Is Climate Change a priority to you and your organisation?

The BBC interviewed 30,000 people around the world prior to COP26. 56% wanted their politicians to take a leadership role and 58% wanted ambitious targets to be met.⁸

For those in the UK, climate change is the single most important issue according to an Ipsos MORI Poll with 4 out of 10 placing it at the top of the agenda. The over-55s have the highest concern for the environment, with 47% citing it as a major issue, compared to 43% of those aged 35-54 and only 27% of the 18-to-34 age group, who ranked COVID-19 as a bigger issue.⁹

This is endorsed by the graph below which shows that there is an acceptance that climate change is real and present.

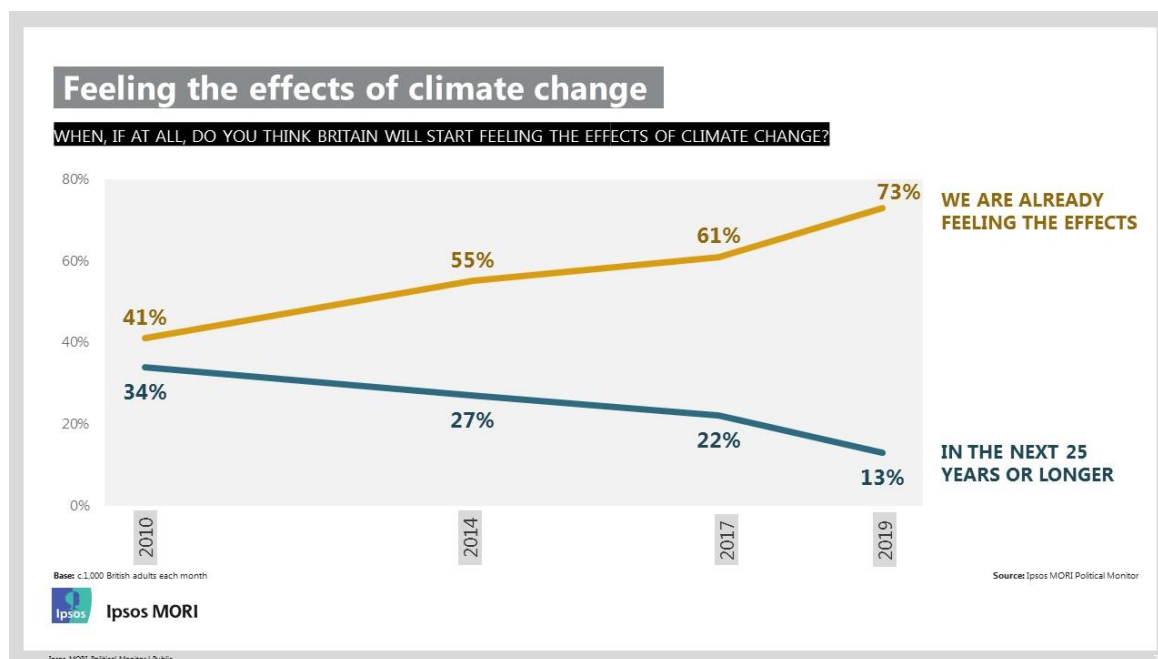


Figure H.9: Opinion poll on the effects of climate change (Source: Ipsos)

Over half of the UK's largest businesses have committed to eliminate their contribution to carbon emissions by 2050, representing a total market capital of over £1.2 trillion and

⁸ [Climate change: Polls shows rising demand for government action - BBC News](#)

⁹ [Ipsos Issues Index: November 2021 | Ipsos](#)

combined annual turnover of £700 billion.¹⁰ This contrasts with smaller businesses. When UK businesses were surveyed in 2021 then two thirds (64%) had no environmental sustainability policy.¹¹

Government and local authorities are embracing climate change and the challenge to get to Net Zero by 2050. 91% of local authorities are initiating some form of decarbonisation¹². Furthermore, NAO found that more than one-third (38%) of single and upper tier authorities have adopted a commitment to decarbonise their local area by or before 2030.¹³

From our own research, 30 out of 31 representatives at the Operators Workshop said that climate change was an issue to them of which 17 out of 18 representatives of logistics companies said yes. When a similar question was posed of local organisation representatives in Doncaster and North Lincolnshire 71% answered that climate change was important to their businesses.

This is adding to the argument developed in Section 1 of this report:

- Large organisations are committed because of customer and investor pressure
- SMEs are slower to adopt
- Individuals wish to align with climate change initiatives
- Policy and incentives will impact on adoption

3. **What is the biggest contributor to UK's Greenhouse Gases**

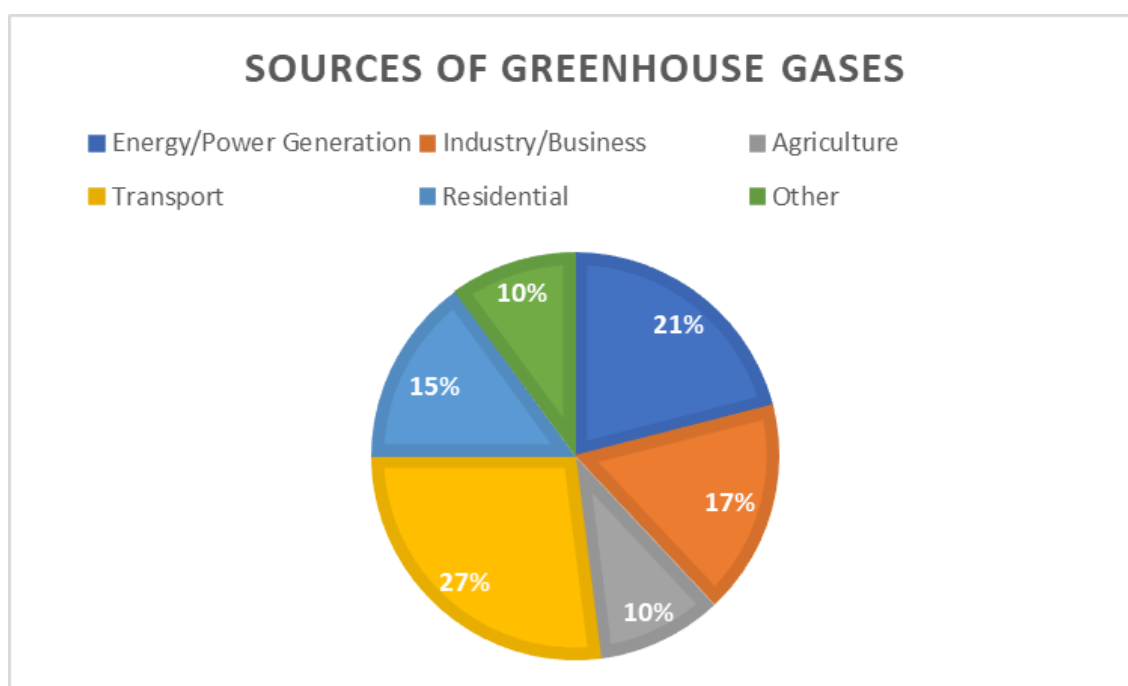


Figure H.10: Relative GHG sources by sector.

¹⁰ [COP26 sees UK businesses lead the world in climate change commitments - GOV.UK \(www.gov.uk\)](https://www.gov.uk/government/news/cop26-sees-uk-businesses-lead-the-world-in-climate-change-commitments)

¹¹ [Two thirds of businesses have no plan for sustainability | The Independent](https://www.independent.co.uk/business/news/two-thirds-of-businesses-have-no-plan-for-sustainability-b1000000.html)

¹² [Local government and net zero in England - National Audit Office \(NAO\) Press release](https://www.nao.org.uk/news/press-releases/2022/local-government-and-net-zero-in-england/)

¹³ ['Serious weaknesses' in government's work with councils on net zero, says NAO | Local Government Chronicle \(LGC\) \(lgcplus.com\)](https://www.localgovernmentchronicle.co.uk/news/serious-weaknesses-in-government-s-work-with-councils-on-net-zero-says-nao/)

Transport is the largest contributor at 27% and is defined as road transport, domestic aviation, railways and domestic shipping. International aviation and shipping emissions are not included in national totals.¹⁴ 15.9% of the transport figure is due to heavy duty lorries which approximates to HGVs being responsible for 4.3% of UK's greenhouse gas emissions. Globally this rises to 7.3%.¹⁵

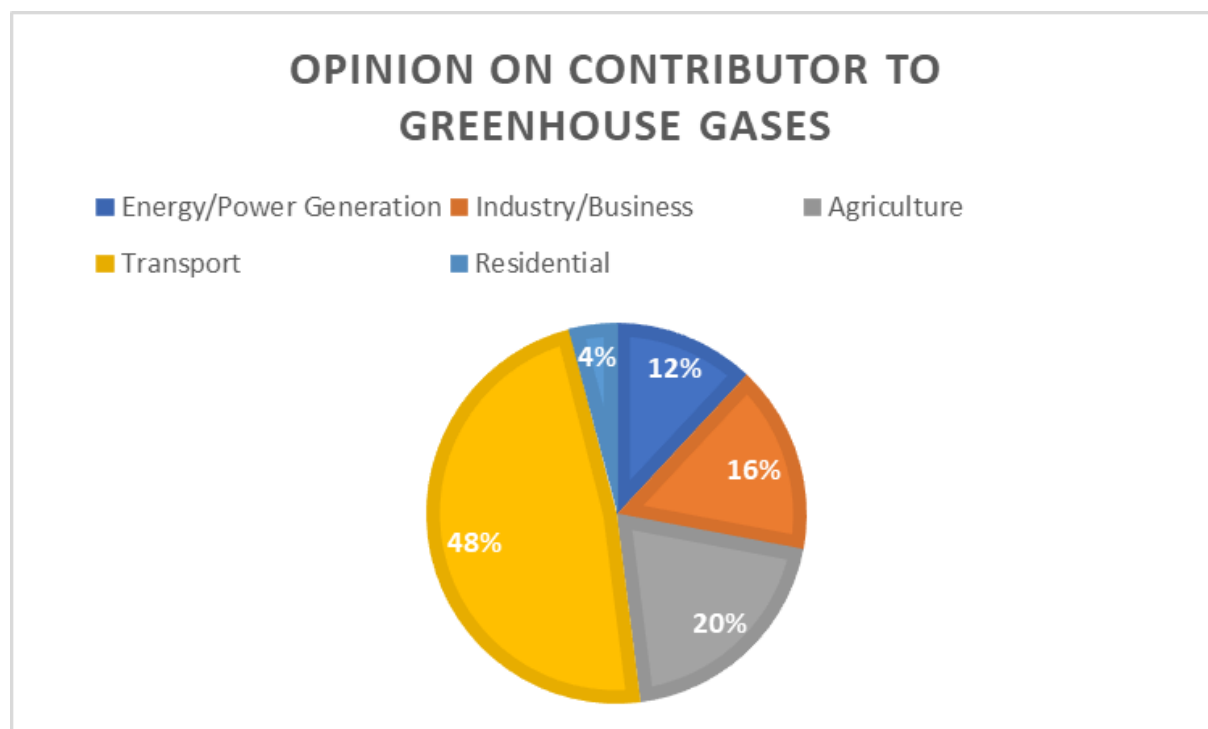


Figure H.11: Opinion poll results on the largest source of GHG.

In the qualitative interview process, a regular question asked was whether replacing diesel lorries with electric ones gave the best bang on the carbon buck. Therefore 25 people were asked to choose from the top 5 sources which they thought was the biggest contributor. It should be noted that 20 out of the 25 did not know at this stage, that a transport interest was conducting the survey.

There is a general awareness that transport is a major contributor but probably not enough to say that transport should be the priority and that lorries within this are a major issue. This would indicate that considerable effort is needed to inform individuals and businesses on the relative importance of market sectors and what the major contributors within these are.

4. Would you buy an electric car?

YouGov conducted a poll in Great Britain in which they found that 43% said that they would be willing to switch to an electric car. However, a policy which would force drivers to make such a change is unpopular, with 46% opposing a blanket ban on the production and sale of all petrol and diesel cars.⁹

¹⁴ [2019 UK Greenhouse Gas Emissions, Final Figures \(publishing.service.gov.uk\)](https://publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/672222/2019_UK_Greenhouse_Gas_Emissions_Final_Figures.pdf)

¹⁵ [Decarbonising Transport – A Better, Greener Britain \(publishing.service.gov.uk\)](https://publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/672222/Decarbonising_Transport_-_A_Better_Greener_Britain.pdf)

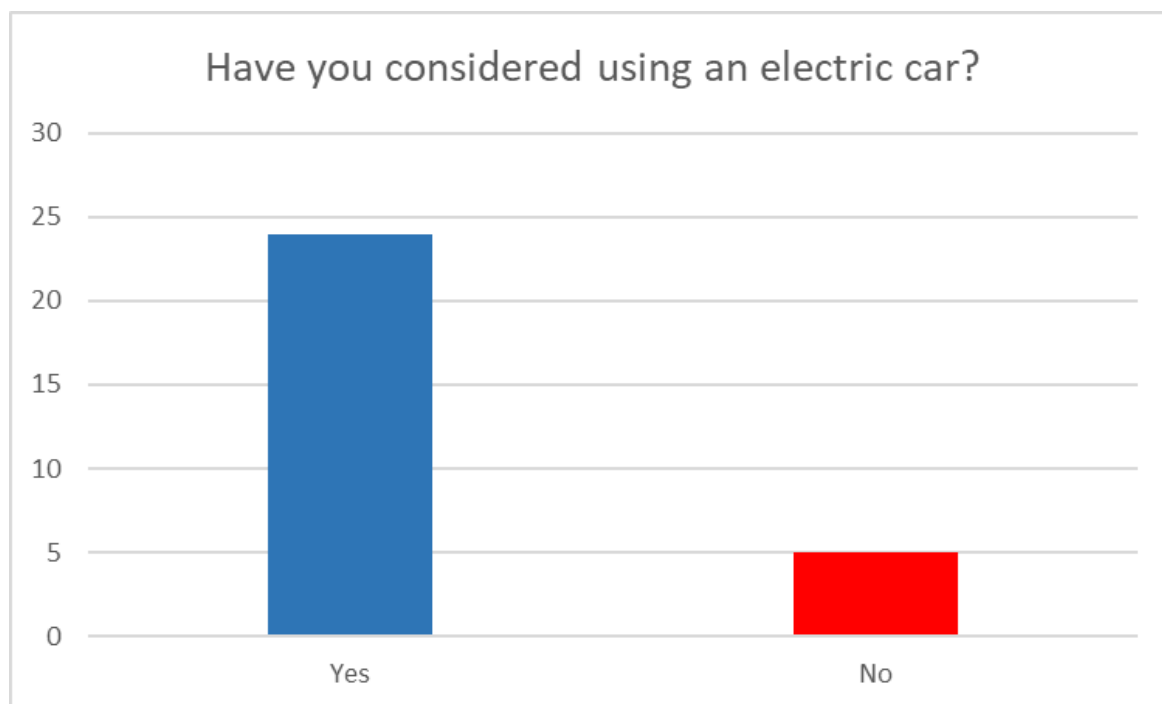


Figure H.12: Opinion poll on electric vehicle purchasing decisions.

This question was posed to the 29 representatives of the 21 businesses interviewed. It sought to drill down into what is motivating individuals and whether the concept of moving to electric vehicles (and therefore to electric lorries) is an acceptable step.

83% of those surveyed said that they had considered switching to an electric car. Interestingly a Director from North Lincolnshire said that he had not but he had been instrumental in providing charge points at his work place.

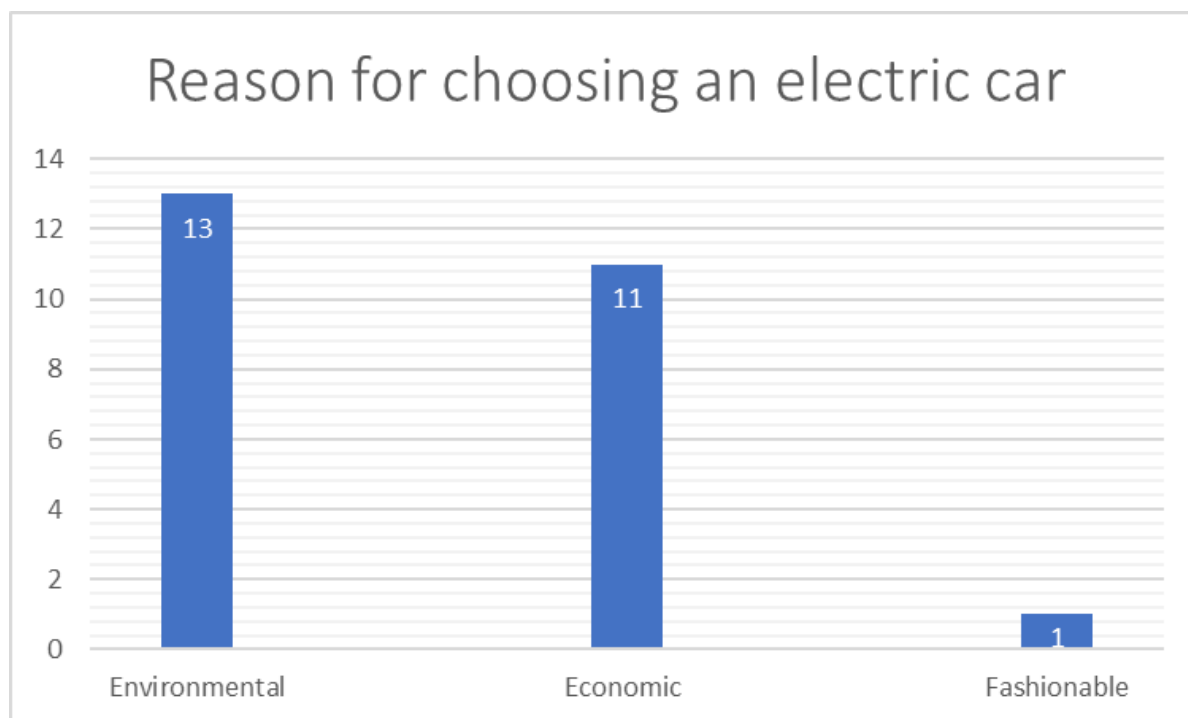


Figure H.13: Opinion poll on electric vehicle purchase reasoning.

It was almost a 50:50 split between environmental and economic why individuals are drawn to driving electric. The environmental factor might indicate the greater good whereas the economic argument indicates that individuals are waiting for an incentive. Only one owned up to following the fashion with the added thought that electric cars were very stylish.

Some of those who said “yes” then added why they had not yet bought an electric car. The overwhelming reason for not buying an electric vehicle was cost (10 out of 15) with 4 suggesting the availability of charging and 1 did not drive.

Although this question was asked of individuals, it also reflects where local and small businesses are at the moment. They are mindful of the environmental need to change but can not make the step unless it is cost effective.

5. **As a Haulage Business what needs to happen for you to switch to ERS**

The indications were good that logistics and haulage businesses were ready for change. In 2020, the LowCVP’s conference survey found that a large majority (91 per cent) of over 200 stakeholders thought that the time was ripe to ramp-up ambition in terms of road transport decarbonisation and that there is an expectation that people are now open to more radical and rapid change.

Although respondents said that the right balance must be found between economic and environmental objectives, nearly 30 per cent also said that environmental concerns should be prioritised even if there is an economic cost. 63 per cent of respondents said a ‘win/win’ can be achieved for the environment and economic recovery if the right policies are implemented.¹⁰

Having established that individuals and businesses are waiting for an incentive to go with their wish to tackle climate change, what do haulage and logistics companies believe is needed to create the right environment to switch to ERS.

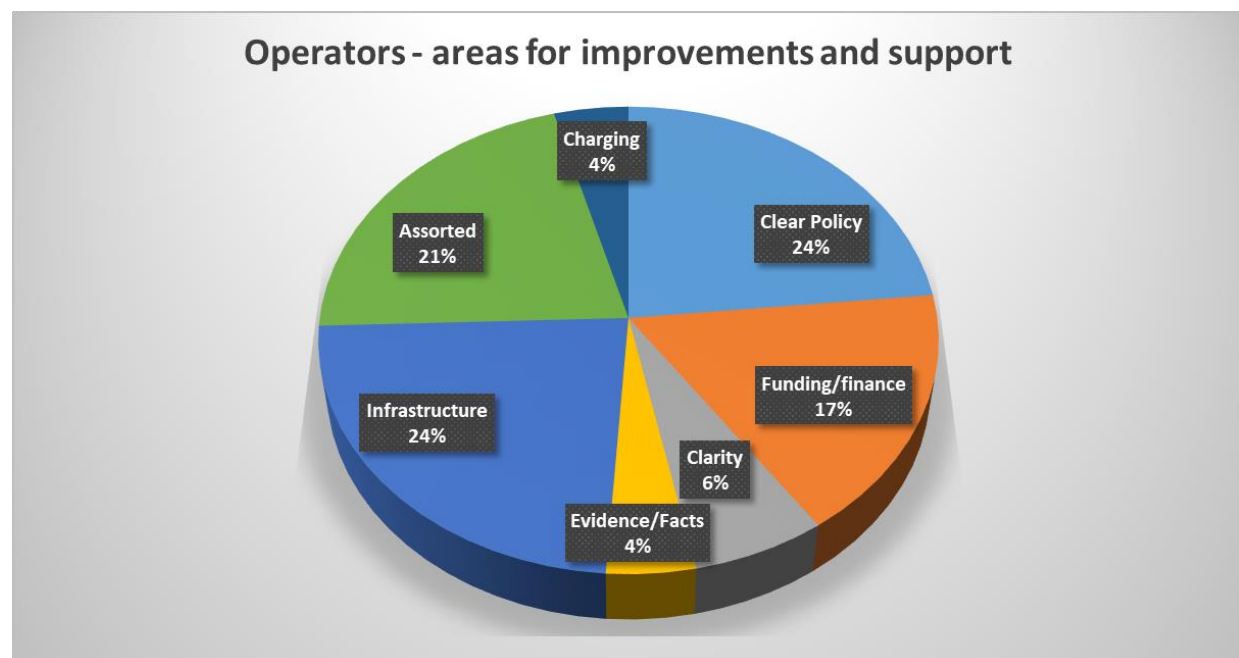


Figure H.14: Areas for improvement and support as requested by operators.

Coming through from the Operator’s workshop, this industry needs a certain level of reassurance to create the confidence that ERS can be supported, namely

- Clear policy

- Infrastructure
- Funding & finance

6. **Do your lorries travel to Europe?**

This initiative started with the premise that that haulage companies should not be adversely affected by ERS. Interoperability (i.e. the ability to travel to Europe) was offered as a concern not only by the industry but also by other stakeholders.

2020 saw 2.3m trips by lorries over 3.5T into Europe. There were also 1.1m unaccompanied trailer journeys.¹⁶ Previously in this report, it was stated that 109,000 of the 413,000 vehicles over 7.5T, were 44 t HGVs. It would be reasonable to assume that around 500,000 trips were made by 44 t lorries to Europe with 1.1m trailers either being delivered or collected to UK ports.

In our survey, 19% of haulage companies send vehicles to Europe on a daily basis and therefore for these companies, they would need Europe to be coming on stream in parallel to the UK or an effective hybrid with a range extender to be developed.



Figure H.14: Survey results of haulage companies on their travel into Europe.

7. **Who owns the lorries?**

Nationally 44% of lorries are owned outright with the 56% using a mixture of leasing and financing arrangements¹⁷. Our group of more blue chip operators had a higher figure of 75% that were leased or financed.

¹⁶ [UK Port Freight Statistics: 2020 \(publishing.service.gov.uk\)](https://publishing.service.gov.uk)

¹⁷ [BVRLA-2020-Industry-Outlook-CV-Final-revised.pdf](#)

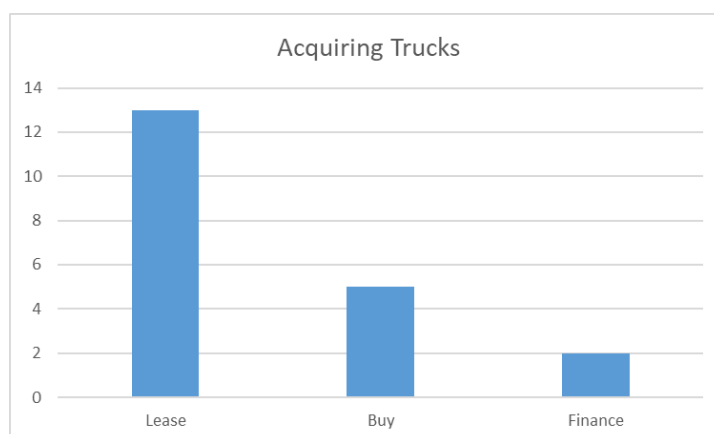


Figure H.15: Lorry ownership survey results.

For these companies the final ownership of the vehicle sits with the leasing company. Therefore, this is an area for further investigation and exploring the appetite for leasing companies who will take the risk on the legacy value of vehicles. In particular, the companies interviewed represented the most likely ones to be early adopters.

8. **Business Reaction to Electric Roads**

Are local businesses likely to object to the potential inconvenience of further disruption to the M180? (The road is currently having its concrete sub-base repaired.¹⁸)

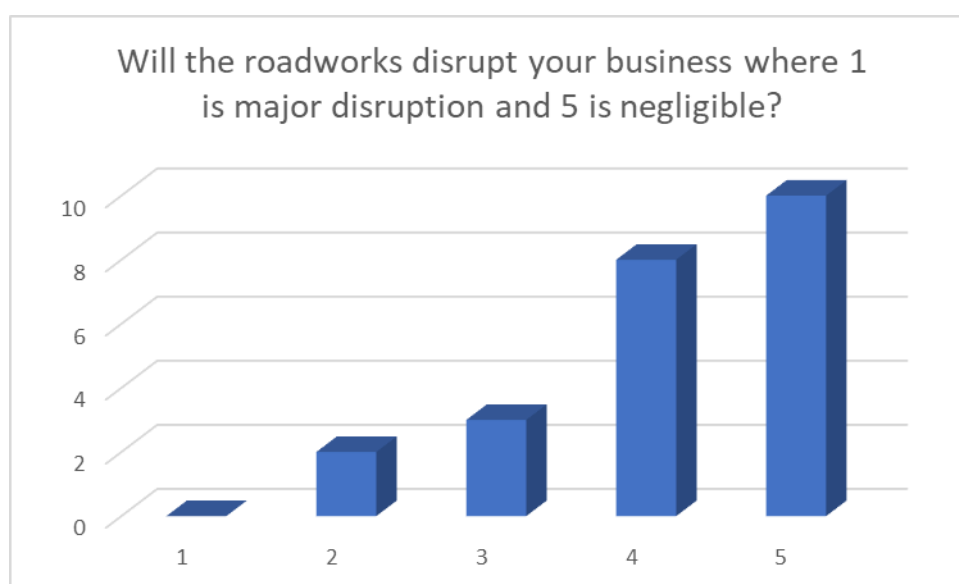


Figure H.16: Survey results on anticipated disruption caused by ERS construction activities.

The 78% response of 4 or 5 to this question was reinforced by a comment along the lines of this is short term pain for long term gain. This stoical response is often recorded on projects where the community can see the much appreciated benefits.

A concern that is regularly raised is one of visual impact.

¹⁸ [National Highways trials new method to increase concrete lifespan on M180 in North Lincolnshire | New Civil Engineer](#)

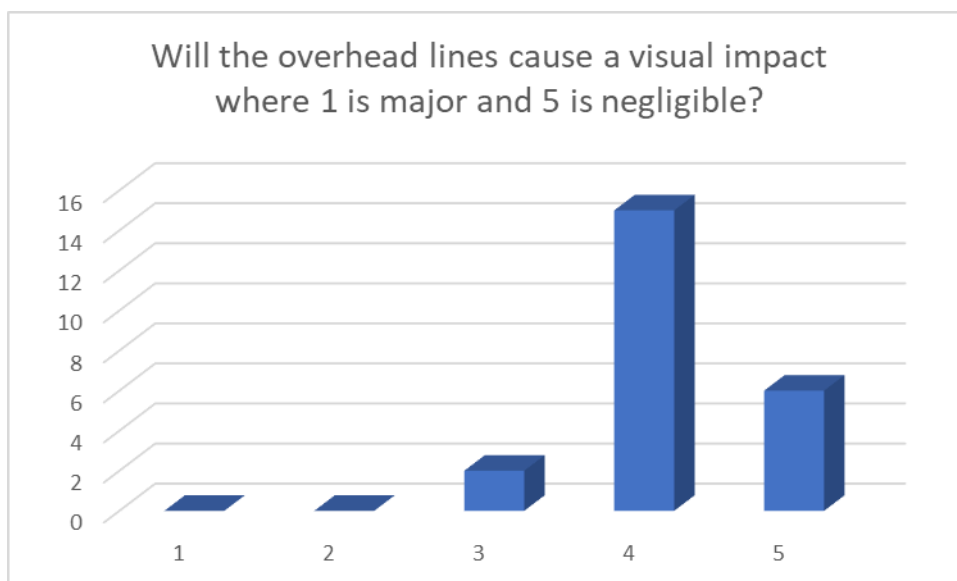


Figure H.17: Survey results on the visual impact of ERS.

91% scored this as a 4 or a 5 – meaning that they did not see it as an issue. This question was batted back by some who regard the road itself as an intrusion and a few lines will not make any difference.

The acid test for local businesses and organisations is whether they will potentially benefit from such an initiative.



Figure H.18: Survey results on the opportunities presented by ERS.

65% (4 or 5) thought that it would afford some opportunity.

COP26

Introduction

The team travelled up for three days to Glasgow from 8 to 10 November 21. 10 November was Transport Day.

The trip consisted of three elements

- Day 1 Scania Conference
- Day 2 Meeting Key People at Arup's Offices and in a Glasgow Restaurant
- Day 3 Visit to the Green Zone of COP26

1. Scania Conference Notes – 8 November 21

Christian Levin (Scania)

He looked ahead and said that Scania was well prepared for the future. It has a well established base of 1,600 dealerships. COP26 was driving the shift to work closer together to jointly find solutions for sustainable transport solutions.

By 2023 we will have 40t lorries that will run for 4 hours before recharging in 40 minutes. There is a need to work with customers (operators) to develop the vehicles and the supporting infrastructure.

Undoubtedly green energy is part of the solution. Having the right network of static chargers is needed. There is needed policies that incentivise use.

Andreas Foller & Jennie Cato (Scania)

It is a question of making it work through large scale adoption. Scania itself is looking to be net zero by 2040 – 10 years ahead of programme. For an electric system to work, there needs to be a roll out of a charging system and for there to be a carrot and stick approach of tax and incentivisation to negate any extra cost of using carbon friendly fuel.

Bob Moran (Department for Transport)

In July 2021, DfT published “Decarbonising Transport”. Transport is evolving and the upside is cheaper, quieter, more efficient and reliable systems. There is a tendency to look towards rail but it is constrained by capacity. However, it does introduce the issue of last mile deliveries.

Power walking and cargo bikes are emerging as solutions along with more innovation and better use of data.

It becomes a numbers game and balancing the practicalities with cost with public opinion.

UK has now in its budget agreement to move forward on trials on its more innovative solutions.

Sarah Muckerjee (IEMA) Institute of Environmental Management & Assessment

Sarah started by comparing different forms of vehicles and their CO₂ emissions.



	% Miles travelled	% CO ₂ Emissions
Cars	78	55
Vans	16	16
HGVs	5	16

Table H.2: Relative proportions of miles travelled and CO₂ emissions from road transport sectors.

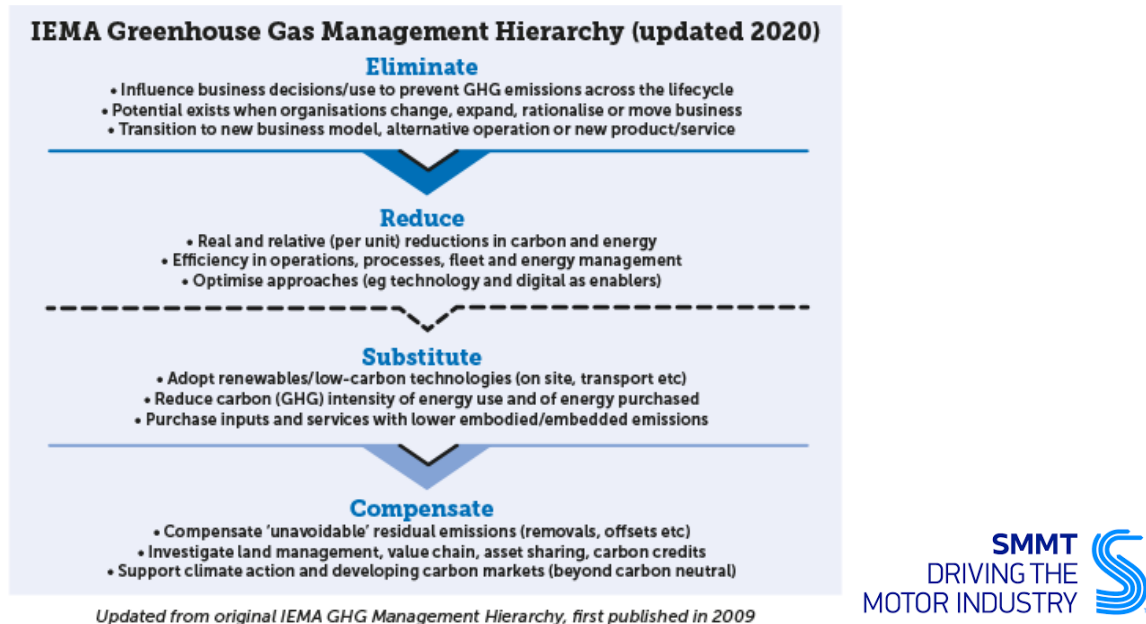


Figure H.19: IEMA GHG Management Hierarchy.

IEMA has a strategy of eliminate-reduce-substitute-compensate.

She questioned whether creating a best way to a net zero solution was through a competitive tendering process. The real challenge is to establish an effective baseline against which time and capacity can be assessed.

Mike Hawes (SMMT)

Mike said that the UK was the home of engineering excellence and therefore should be at the forefront of new technologies.

Rhetorically, he asked how does the country end the sale of fossil fuels. There are roughly 40m vehicles in circulation with an average life of 9 years and cars 14 years. There is a backlog of new cars caused by the shortage of semi conductors.

The roll out of any solution is fraught with complexity and there is no silver bullet.

Graeme Cooper (National Grid) includes individual meeting notes

Graeme advised that any proposal to NG should relate to its Mission, Vision and Values. "Market enablement" is a key expression. NG tends to take a steering, light touch role.

NG is a conduit of energy – it neither buys nor sells energy. However, this does not absolve it from its responsibilities and is aware of the Commission for Climate Change's projections for 2040:

- 2 x energy consumption.
- 4 x clean generation (renewables and nuclear).
- 2 x grid capacity.

The current grid can cope – over the last twenty years the peak demand was in 2002 (62GW) compared to lockdown demand of 30GW. Despite heating being 83% dependent on gas, it is transport which has the priority. This will move demand for renewable energy from 10GW to 40GW. The current energy demand fluctuates over the course of the day. Interestingly many of the offshore wind transmission concessions are seeking hydrolysis permits i.e. the capability to store energy. The peak demand is around breakfast and tea.



Figure H.20: The electricity supply grid and road network

The rapid charging fund (RCF) is a £950 million fund to future-proof electrical capacity at motorway and major A road service areas to prepare the network for 100% zero emissions vehicles (ZEV) uptake.

It is very innovative and this will take thinking onto catenary systems for HGVs. Interestingly over 60% of NG power lines follow the road system. How and where vehicles charge off the network will be a challenge. Therefore, it will be a question of getting the right product, the right fuel and delivering at the right time.

MSA will ultimately require a 20 MW connection which is the same size as a medium sized town. The immediate plan is for 1 MW connection which will be upgraded to 8MW. However, Graeme trotted out the expression more than once “do it right, do it once”. The extra cost of making a connection for all vehicles is marginal.

NG has a long lead in time – 3 years. So future planning needs to take this into consideration.

Graeme was keen to emphasise on three separate occasions that “money has a conscience”. Increasingly investors are looking for ethical outlets with a green agenda. Pension funds tend to look for low risk opportunities. NG can help by pump priming.

Will Wilson (Siemens Mobility)

Will’s overriding message was that the country required a spine of the right infrastructure to create a new solution and in particular, Electric Road System.

Bio Fuels

Four representatives led the way – Philip Fjeld, David Hurren, Dickon Posnett and Magnus Hammick. In subsequent discussions what seemed an obvious solution of using biofuels as an environmental solution was explored. Biofuels had received bad press due to developing

countries sacrificing food production in favour of fuel and exports. However, Philip Fjeld was keen to emphasise that all his fuel comes from local waste¹⁹.

There is insufficient local biofuel to drive UK's entire HGV fleet, however it may be possible to develop a hybrid and therefore use biofuels as a range extender.

Paul Smith (Summary)

- We can do this
- Partnering @ scale
- Policy and incentives
- Address today and tomorrow's fleet
- Cross cutting infrastructure

¹⁹ [Why Biomethane is The Fuel of Today And Tomorrow - Mobility Moments With CNG Fuels' CEO Philip Fjeld - Auto Futures](#)

2. Connecting with Key People

COP26 has taken the move to arrest climate change to a new level. A momentum seemed to be being created in November 2021. This was allowing ERS to gain traction and the team was encouraged to work collaboratively with all related groups and rail.

Those that attended either one or both of the two events were as follows:

Virginia Bath	CSRF
Alan Belfield	Arup
David Cebon	Cambridge University
Ian Constance	Advanced Propulsion Centre
Graeme Cooper	National Grid
Leon Daniels	CILT
Tim Embley	Costain
Simon Flint	Costain
Peter Harris	UPS
Julia King	Committee for Climate Change
Laura Lane	UPS
Justin Laney	Waitrose
Caroline Low	DfT
Hannah Marsh	Siemens Mobility UK
Rod McKenzie	Road Haulage Association
Alan McKinnon	KLU
John Miles	Cambridge University
Bob Moran	DfT
Justin Moss	Siemens Mobility UK
Tanya Neech	Scania
Philip Roe	DHL
Ralph Smyth	Possible
Gerrit Stumpe	Siemens Mobility Germany
David Wells	Logistics UK
William Wilson	Siemens Mobility UK
Paul Wilson	Connected Places Catapult

During the course of the day, those attending were given an update paper²⁰. John Miles and David Cebon presented an overview of WP2 and WP4. They introduced the concept of the Demonstrator Project on the M180. This was to be a “Living Laboratory” in which technological and logistics solutions would be tested. All stakeholders (OEM's, vehicle operators, freight customers, service providers, etc) would be able to explore the potential for ERS-enabled electric vehicles and to test them against their own business needs.

For Haulage and Logistics companies, the offer needs to be commercially attractive. However, businesses must not be adversely affected, and this means that ERS needs to find ways to enable smooth, predictable and timely journeys.

There are big contrasts in the industry. At one end are the large corporate businesses that have shareholders to satisfy and indeed “net zero” targets to meet. Interestingly, there is an

²⁰ “Why Heavy Road Freight Should be Electrified” by John Miles, Phil Greening, Chris Thorne and David Cebon of Centre for Sustainable Road Freight; November 2021

increasing pressure for ethical investment and therefore these larger corporates are seeking justification to make a move to an environmentally friendly system.

At the other end are the owner operators who are more interested in day-to-day operations than long term environmental issues. These include driver shortages and therefore the need to improve the network of support facilities which might lead to better recruitment.

The transition phase continues to be an issue for operators and a believable hybrid will need to be developed. For some bio-methane offers a good and green solution as a range extender.

DfT was upbeat and believed through partnership the next stage is doable. ERS is generally liked in Whitehall. The upside is a global opportunity and the challenge will be to define this to businesses. The overall scheme will need to demonstrate value for money.

ERS is an opportunity to demonstrate an energy efficient and cost effective method of transporting freight. For the sceptics, then proof will be needed that it can be delivered. The reassurance is that it can use the experiences of previous trials and rail to deliver a solution which has a minimum of disruption using an experienced supply chain.

3. The Green Zone

This was somewhat disappointing as there was limited content. Nevertheless, contact was made with the stands of National Grid, SSE and Hitachi. In addition, there was an outdoors stand of JCB.

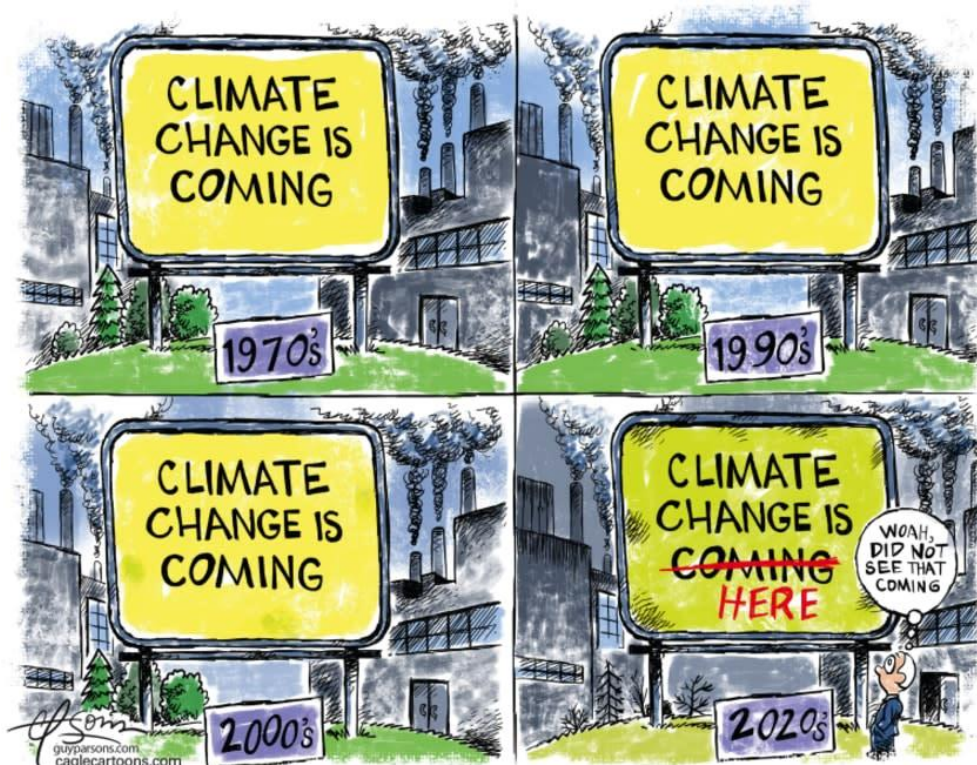


Figure H.21: Climate change cartoon

COP26 Reflections – A Personal View

Boris Johnson opened up COP26 with “if Glasgow fails then the whole thing fails”. For us looking at an eHighway solution, Glasgow was a huge success. We started to tease out the issues and had some meaningful discussions with the ultimate decision makers – the logistics and haulage users.

There is a tendency to take a moral and ethical view. “Money has a conscience” was an expression used by National Grid’s Graeme Cooper. Investors want more than a financial return, they are looking for the added value of supporting environmentally friendly organisations.

However, a few beers in my local pub, the Bricklayers Arms, would reveal that individuals are more concerned with interest rates and the impact on mortgages than a politicians’ generated agenda. In the same way, the Kenyan villager is dependent on her Kerosene cooker to prepare her vegetables.

These people are not wrong for having different priorities and will join the party when they are and more importantly the world is ready to provide them with manageable solutions.

In the same way, we heard from a range of operators and their representative bodies. On the one hand, there are the large fleet operators who are able to take a longer-term view. Conversely, there is the owner operator who is not sure whether the next depot is going to have adequate restroom facilities, let alone what the world will look like in 2040.

For David Wells, UK Logistics, the world of HGVs can be broken down into a 20:60:20 split. 20% are wedded to change and are driven by the COP26 agenda. 60% are more cautious – understand the necessity but require far more certainty. The remaining 20% are either sceptical or believe that it is not an immediate priority for the business.

My view is that we need to work closely with this leading 20% to deliver a meaningful concept that the remaining 80% can follow. We cannot do this from the outside but we need to engage and integrate our thinking with the 20% progressive users, the policy makers and the stakeholders.

Repeatedly we heard that there is “no silver bullet” and yet in this Amazon Prime world of next day delivery, we need a convincing strapline. Consequently, we need a clear vision of the future with a “carrot and stick” mix of policy and incentive. We will need clarity and all interested parties will have to define their piece of the jigsaw to provide Costain’s Tim Embley with the complete picture.

Siemen’s Will Wilson would like to see integrated infrastructure creating a backbone for change. It is this theme of integration that was translated by DfT to mean partnership and was one of Paul Smith’s (Scania) key summary points.

One of the big challenges for an eHighway or the electric road system is the transition period. 2040 steady state is reasonably easy to design but how do we get there? What are the stepping stones that are needed to ensure that businesses and the public are not unduly affected.

Scania’s day saw a mix of vehicles and technologies. The transition period demands a hybrid vehicle, one that will allow HGVs to go about their business off the incomplete network. Therefore combining electric HGVs with biomethane or hydrogen cost effectively appears to be a viable solution.

Returning to Paul Smith's closing remark and paraphrasing it with Caroline Low's (DfT) comment – This is doable in partnership.

Simon Flint, the author, is a member of the Electric Road System Consortium but these are his own opinions and do not represent the policies or strategies of the ten member organisations.

Section 3: Conclusions

1. Introduction

There is an overwhelming sense that climate change is real and needs to be addressed. Diesel lorries contribute 4.3% to the UK's greenhouse gas emissions. In general, ERS was well received by the stakeholders although they did express different concerns. For the general public, the concern is about disruption during construction. However, these can be traded against the long term environmental benefits.

The purpose of this exercise was to gauge opinion from a wide range of people and interest groups.

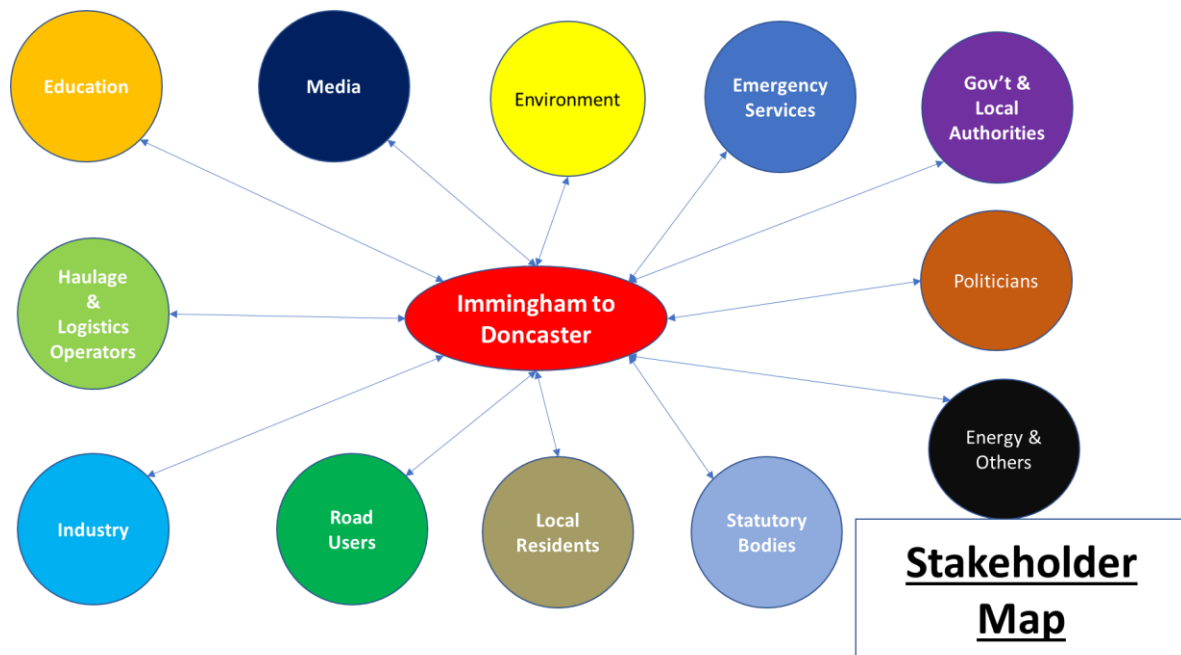


Figure H.22: M180 demonstrator stakeholder map

By the end, most areas were covered although the Politicians category was a little light. Around 100 organisations were consulted in one form or another. These insights were reinforced by two events at COP26 and the CPC Report in September 2020. The map above is conspicuous by the absence of one key stakeholder – National Highways. This account was handled outside this programme through a series of monthly liaison meetings.

Various themes were established and the future steps will be to respond to these challenges and to inform and influence all stakeholders on the merits of an Electric Road System.

2. Key Themes

There are two key stakeholders and both of these need to be comfortable with the principles for there to be firstly a viable Demonstrator project and secondly a successful roll out. They are National Highways and haulage and logistics operators.

National Highways is cautious about the ownership of the power supply and the overhead lines and therefore who is responsible for the safety and the maintenance of the system. The

operators need reassurance that their business model will not be unduly affected by a less flexible system and a different cost base. The key themes were:

- a. Safety
- b. Disruption during construction
- c. Costs
- d. Carbon savings
- e. Government Policy

COP26 was encouraging and emerging from this were five key messages:

- Replacing diesel lorries with ERS is doable
- Collaboration of all interested parties is needed
- Policy and incentives will be needed to allow planning with certainty
- The Fleet will have changing requirements over the next 20 years – diesel to transition to steady state
- Investment in infrastructure that provides confidence

3. Haulage & Logistics Industry Profile

The Haulage and Logistics sector is roughly divided into 20% who are committed to change; 60% who are waiting to see which way the market will go; 20% who are sceptical. The sector has a long tail of small family owned businesses. Between 2022 and 2040 (when diesel lorries will no longer be for sale) there will be 4 to 5 buy and sell lorry cycles. Therefore, for businesses, which are more concerned about surviving the year, ERS development is not relevant.

The initial “buy-in” is going to come from the 20% early adopters. These are corporates which have an environmental policy and have pressure from investors and customers to change.

4. White Elephants and Bang for the Buck

Proceeding with ERS will be a political decision. Advisers have concerns over the cost and whether the large capital investment will be overtaken by changing and emerging technology. The more radical would like to see a fresh approach to how the UK transports goods around the country. There is an in built belief that rail can solve this which does not take into consideration the lack of capacity on the current system.

Nevertheless, any investment needs to be justified over its full life. A decision today needs to be still relevant in 2060. A figure of £20embodied was used for the capital investment required to roll out ERS. This caused concerns of whether it would be overtaken by new technology, changing transport and/or changing consumer patterns. Any one or more of these would render the scheme obsolete and therefore creating a “white elephant”.

Others wanted reassurance that with limited funds, ERS would represent value for money. Relative to other greenhouse gas contributors e.g. steel and cement manufacture, is ERS a priority. In other words they wanted to maximise the Carbon “Bang for the Buck”.

5. Outside the Demonstrator Project

The objective of the Demonstrator Project is to show that all current (and anticipated future) road-based logistics requirements can be met by electric vehicles with a combination of ERS and static charging technologies.

This only partially embraces the challenges that were being made by some stakeholders who wanted a “Proof of Concept” dimension. The areas for further work will include:

- National traffic modelling
- Energy demand modelling
- Future consumer patterns
- Delivery of infrastructure
 - supply chain capacity and capability
 - ability to deliver on time and to budget
- Funding & financing modelling
- Transition options including hybrid HGVs
- Battery development modelling
- Business modelling of haulage and logistics companies
- Policy and Incentives to create change

6. Collaboration

There is a sense that all stakeholder groups want there to be a solution. To create a doable deliverable network by 2040, it will require progressive individuals from a range of backgrounds to work together

Recommendations

1. A full programme is undertaken of informing and influencing key stakeholders on the advantages of ERS – namely:
 - Technology readiness
 - Carbon footprint
 - Energy efficiency
2. Politicians are fully engaged in the above process
3. The larger corporate haulage and logistics companies are embraced to deliver a logistics solution for ERS. This will include provisions for the transition phase.
4. A working group of senior industry people, representing different interests, are assembled to identify a strategy to overcome the key challenges.
5. As part of the Demonstration Project, a visitor centre is included to encourage interest and participation in the initiative
6. A full stakeholder engagement programme is implemented for the Demonstrator Project which helps for all groups to visualise the future opportunity.
7. Local sources of renewable energy are able to be included in construction and operational plans.
8. An assessment tool is drawn up that can effectively compare the costs and carbon impacts of the rival technologies
9. Disruption is kept to a minimum and therefore the impact on villages lining the M180.
10. The Demonstrator Project needs a parallel project to develop “Proof of Concept”. The areas for further work will include:
 - National traffic modelling
 - Energy demand modelling
 - Future consumer patterns
 - Delivery of infrastructure
 - supply chain capacity and capability
 - ability to deliver on time and to budget
 - Funding & financing modelling
 - Transition options including hybrid HGVs
 - Battery development modelling
 - Business modelling of haulage and logistics companies
 - Policy and Incentives to create change
11. Work is continued on developing the concept of a ribbon of excellence along M180 to service ERS, the construction industry, offshore wind and lorry manufacturing. This would be based on the proposed Freeport at Immingham, British Steel at Scunthorpe and the logistics hub at Doncaster.

Acknowledgements

The following Organisations were interviewed and contributed to the gauging of opinion:

Consulted

BBC Humber
BEIS
Bradbury Group
British Steel
Burgess Salmon
Cambridge University
CIHT
CILT
CMG
DfT
Doncaster Council
Duncan Plant Hire
East Midlands Ambulance Service
Edinburgh University
Environment Agency
Greater Lincolnshire LEP
Heathrow Expansion
Hitachi Energy
Humber Freeport
Humber LEP
Humber Police Force
Humberside Fire Service
ICE
IET
Intent Group
IPA
IUK
IVA
JCB
KPMG
Lantern
Leeds University
Lincolnshire County Council
Local Resilience Forum
Logistics UK
Macquarie
Manchester University
Mayor of Doncaster
Midhurst Engineering
Mike Boniface Engineering Ltd
National Grid
National Highways
Nestle UK
North East Lincs Council
North Lincolnshire Council
Northern Powergrid
Ofgem
Port of Immingham
RAC Foundation
Rainham Steel
Road Haulage Association

Rockscape
Rotary Club of Doncaster
RSPB
Scawby Parish Council
SMMT
South Yorkshire Mayoral CA LEP
SSE
Synaps Ltd
Tractor Exports Ltd
Transport Focus
Transport for North
Ulceby Action Group
Ulceby Parish Council
WSP
Yorkshire Humber Climate Commission

Operators Workshop

BUNZL
DfT
DHL
Hermes
Howard Tennens
Logistics UK
Mint Green Sustainability
Morrisons
Nestle
Retail Energy Forum
RHA
Sainsbury
Smiths News
SMMT
Travis Perkins
UPS
Wickes
Wincanton

Doncaster Businesses/Organisations

Alus Services Ltd
Bhayani HR & Employment Law
Co-Operative Bank
Doncaster Chamber of Commerce
Doncaster College
Doncaster Deaf Trust
IMSM
JST Group
North Lindsey College
Remondis
Smarta Tutoring
Solutions 4 Cleaning
S-P-L Specialist Project Logistics
Taylor Bracewell
Techni Measure
Unimax Solutions