Zero Emission HGV Infrastructure Requirements

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Report for Committee on Climate Change

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Executive Summary

Battery electric vehicles (BEV) are commonly accepted to be the most promising technology for decarbonising the light duty vehicle sector. However, the most cost-effective route to decarbonising the heavy-duty vehicle (HDV) sector is much less clear, with electric and hydrogen options emerging as viable alternatives to diesel. It is expected that battery electric or hydrogen HDVs could be available in the 2020s, and with rapid uptake possible once they reach total cost of ownership (TCO) parity with diesel, uptake of zero emission options could accelerate rapidly. This would have a significant impact on the UK's transport infrastructure. The Committee on Climate Change (CCC) commissioned Ricardo Energy & Environment ('Ricardo') to carry out research to assess the infrastructure requirements and costs for different zero emission HDV options up until 2050, or as soon as practical thereafter.

The technologies considered are:

- Hydrogen refuelling stations (HRS) for hydrogen fuel cell electric vehicles (FCEVs)
- Ultra-rapid charge points at strategic locations for battery electric vehicles
- Electric road system (ERS) infrastructure, namely overhead catenaries for battery electric or battery hybrid vehicles
- Hybrid solutions, combining elements of the above.

We considered three size categories of HGVs in our modelling, consisting of small rigid, large rigid and articulated HGVs. We used a scenario-based approach, with each technology-focused scenario representing a push towards a certain powertrain technology type. The market shares of different powertrain technology types were estimated for each scenario. Six scenarios were analysed:

- Scenario 1 – Hydrogen
- Scenario 2 – Battery electric vehicles [BEV]
- Scenario 3 – Battery ERS
- Scenario 4 – Hydrogen ERS [H2 ERS]
- Scenario 5 – Hydrogen range extender [H2 REX]
- Scenario 6 – Plug-in hybrid electric vehicles [PHEV].

These are compared with a baseline which assumes continuing diesel use across the sector.

The model utilised an energy-based calculation to determine the number of point-based infrastructure units (such as ultra-rapid chargers and HRSs) and an HGV flow-based calculation to determine the most intensively used roads for ERS installation. This led to the overall infrastructure requirements for the HGV fleet to 2060. The main outputs from this model are the infrastructure costs (annualised, in-year, CAPEX, OPEX and NPV for society and on a private basis) and the infrastructure build rate requirements to achieve full decarbonisation by 2060. The project also considered issues around build rates and other infrastructure changes needed to deliver these scenarios. However, vehicle costs and network costs (e.g. electricity network upgrades) are not in scope for this study. Therefore, costs presented here are only part of the overall costs that should be considered when determining total cost effectiveness of the scenarios.

Box 1: Main Results

- The most cost-effective zero emission option in terms of infrastructure costs is the Hydrogen scenario, which has a cumulative CAPEX cost of £7.7bn in 2060, compared to £11.4bn for the Battery scenario and £10.41bn for the Bat-ERS scenario (with depot chargers comprising a large CAPEX proportion for each of the scenarios).
- The annualised costs (including fuel) for all scenarios are lower than the baseline. This shows that although the zero-carbon options (i.e. excluding PHEV) have high up-front costs, their annualised costs are 38% to 52% lower from a societal cost perspective than the fossil fuel comparator by 2060. This is driven by higher efficiencies (particularly for Battery & ERS scenarios) and lower unit costs of zero carbon fuels.

- In these scenarios, 4,100 HRS would need to be built by 2060 for the Hydrogen scenario, 908 ultra-rapid chargers for the Battery scenario and 3,850km of ERS infrastructure by 2060.
- The cost of electric infrastructure (Scenario 2) is dominated by depot chargers due to the requirement for these to be rapid in order for the large vehicle batteries to fully recharge overnight.
- In all scenarios, this infrastructure would support a ramp up to almost 400,000 zero emission HGVs by 2060 (total of UK parc).
- Moving to zero-carbon infrastructure for HDVs is a significant challenge and requires planning, co-ordination, supply chains, resource and materials and a skilled workforce as well as strong government policy to enable the market to deliver. However, our analysis and discussion with stakeholders found that the infrastructure required to serve scenarios reaching a near zero HDV fleet by 2050-2060, could be delivered.
- There is no clear market preference for long-haul electric or hydrogen HDVs at this time. Both options can be used to deliver the levels of freight service and efficiency currently provided by diesel vehicles. There does appear to be a clear preference for smaller electric HDVs.

Infrastructure costs

The baseline scenario represents a continued reliance on diesel infrastructure, with no new investment made in the period considered. This implies that CAPEX for the baseline is negligible; as such, any infrastructure investment costs presented here are in addition to the baseline values.

From a cost perspective, the Battery infrastructure scenario represents the least cost investment option for a transition to zero emission HGVs by 2060[1]. This is shown in the Figure ES1 and Table ES1 below, which compares the infrastructure and fuel costs for all scenarios.

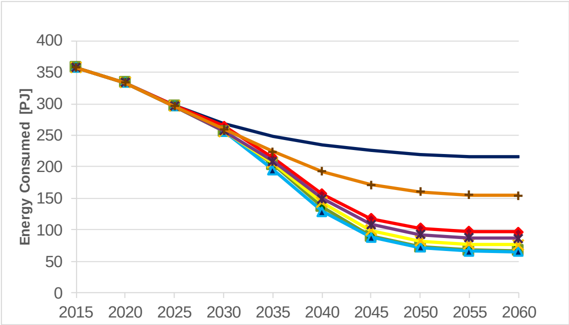
All scenarios have lower fuel costs than the baseline scenario based on CCC long-run fuel cost assumptions. We assume there are no additional CAPEX costs associated with continuing fossil fuel use in the baseline. The infrastructure costs for the zero carbon scenarios are mostly in a relatively similar range/magnitude up to 2050, with greater divergence after this. A high proportion of the CAPEX costs (cumulative to 2060) of the infrastructure (48% for Bat-ERS, 93% for Battery and 100% for PHEV) for the electric scenarios is due to depot chargers (compared to 2% for Hydrogen and 4% for H2-ERS; though depot chargers make up 43% of infrastructure costs for the H2-REX scenario). For HGVs, many of these need to be higher powered than those currently used for light duty vehicles due to the large batteries and the requirement to fully recharge the vehicles overnight – this leads to a large need for DC charging (>50kW). With a requirement for more than 340,000 chargers in 2060 for the battery scenario, these costs are very high. Conversely, the number of ultra-rapid chargers (>150 kW) is relatively low, with a requirement for 900 to be installed throughout the UK in the Battery scenario by 2060. The other electric scenarios do not[2] require ultra-rapid charging.

For the ERS battery and H2-ERS scenarios, there is a trade-off between the deployment of depot chargers and HRSs with one effectively replacing the other in their respective scenarios. However, the required length of the ERS system on major roads is very similar in these two scenarios.

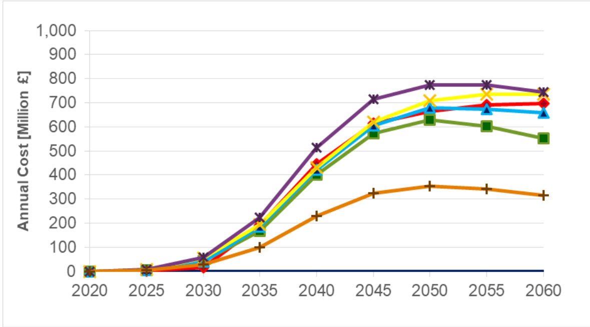
Fuel costs are very significantly higher than annualised infrastructure costs for all scenarios, with the lowest costs for the Battery and Bat-ERS scenarios through to 2060, and higher in all other scenarios. Fuel costs are significantly higher (~2-7 times) than annualised infrastructure costs in the Hydrogen and PHEV scenarios. As a result of this, the Battery scenario (and then Bat-ERS) is the lowest cost zero carbon option for all periods when considering both infrastructure and fuel costs[3].

[1] The initial project brief requested calculations up to 2050 or 'until it is feasible and cost-effective for 100% of the fleet to have transitioned to new technologies'. Based on initial modelling results, the time period was extended to 2060.
[2] The model output for Battery-ERS scenario predicts that one ultra-rapid charger is required, which can be considered negligible.
[3] Sensitivities for infrastructure costs are considered in the report, but not for fuel costs. Vehicle costs are not included here.

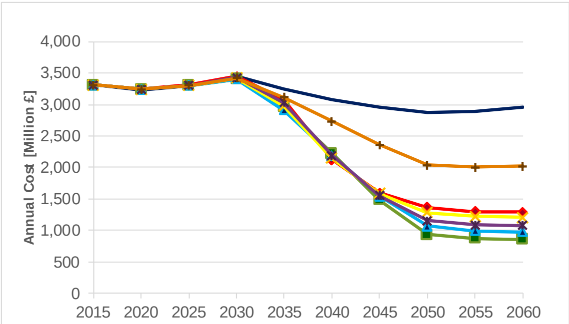
Figure ES1: Cumulative energy and CAPEX results for infrastructure at 2060 for each scenario



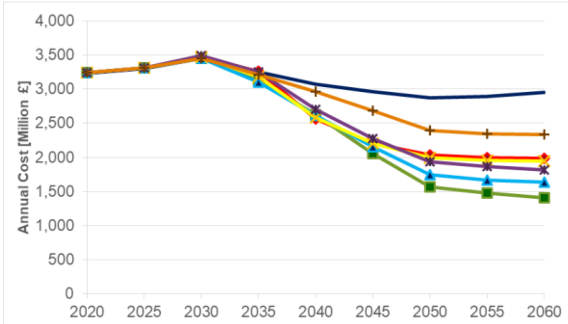
(a) Energy Consumed [PJ]



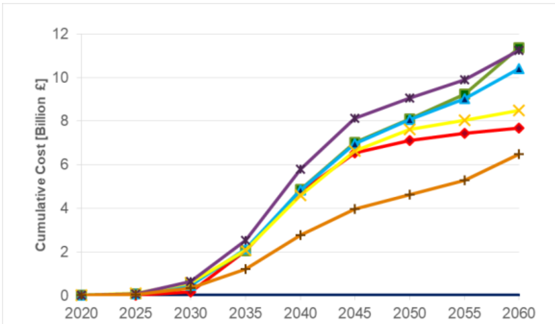
(b) Total annualised infrastructure cost p.a. (societal) [Million £] (1), (2), (3)



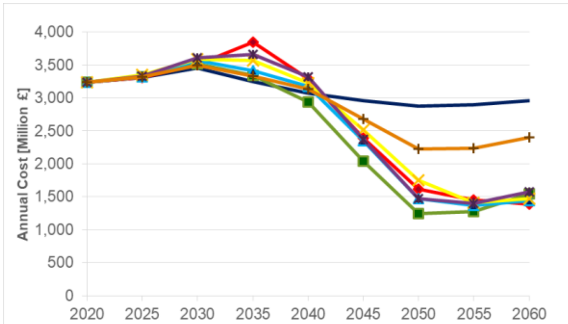
(c) Total annual fuel cost (societal) [Million £] (1)



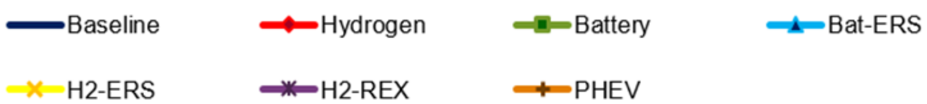
(d) Total annualised fuel and infrastructure cost (societal) [Million £] (1), (2), (3)



(e) Cumulative CAPEX infrastructure costs (societal) [Billion £] (4)



(f) Total in-year fuel and infrastructure cost [Million £] (1), (4)



Notes: (1) Societal costs exclude all taxes. (**2**) The societal annualised cost calculations use a discount rate of 3.5%, and exclude all taxes. Annualised costs calculations convert capital expenditure into annual repayment costs over the relevant payback period (taken to be the infrastructure lifetime for a societal basis); where fuel and infrastructure operating costs are also included these are the average total costs of expenditure for a given year. (**3**) Total infrastructure costs include both the up-front capital expenditure (CAPEX) as well as operation and maintenance costs (OPEX). (**4**) In-year cost estimates do not include any annualisation of CAPEX costs, and simply represent all expenditure for the specified year.

Table ES1: Headline results for each scenario at 2060 (2018 prices)

Scenario	Energy Consumed [PJ]	Annualised infrastructure cost at 2060 (societal – 3.5% discount rate) [Million £]	Annual fuel cost at 2060 (societal) [Million £]	Annualised fuel & infrastructure cost (societal) [Million £]	Cumulative CAPEX by 2060 (societal) [Bn £]			Cumulative total in-year costs by 2060 (including OPEX and fuel) (societal) [Bn £]		
					Low	Default	High	Low	Default	High
Baseline	216	£-	£2,954	£2,954	£-	£ -	£-	£148	£148	£148
Hydrogen	97	£698	£1,291	£1,990	£5.82	£ 7.7	£9.52	£129	£133	£137
Battery	67	£553	£858	£1,412	£10.74	£11.4	£12.07	£123	£123	£124
Bat-ERS	66	£660	£980	£1,640	£9.60	£10.4	£11.73	£126	£128	£130
H2-ERS	76	£735	£1,209	£1,943	£6.96	£ 8.5	£10.50	£129	£133	£138
H2-REX	86	£743	£1,074	£1,817	£9.73	£11.3	£12.83	£129	£132	£135
PHEV	155	£316	£2,021	£2,337	£6.14	£ 6.5	£6.85	£139	£140	£140

Notes: (**1**) Societal costs exclude all taxes. (**2**) The societal annualised cost calculations use a discount rate of 3.5%, and exclude all taxes. Annualised costs calculations convert capital expenditure into annual repayment costs over the relevant payback period (taken to be the infrastructure lifetime for a societal basis); where fuel and infrastructure operating costs are also included these are the average total costs of expenditure for a given year. (**3**) Total infrastructure costs include both the up-front capital expenditure (CAPEX) as well as operation and maintenance costs (OPEX). (**4**) In-year cost estimates do not include any annualisation of CAPEX costs, and simply represent all expenditure for the specified year. (**5**) Low / Default / High cumulative total in-year costs are sensitivities on the infrastructure costs only; there are no fuel cost sensitivities included.

Build rates

The project considered annual infrastructure build rates required to deliver the scenarios. Build rate limitations are not thought to pose a significant constraint for most scenarios but this is a complex area that requires further research. Transforming current HGV infrastructure is a massive infrastructure challenge and depends on a number of factors such as availability and skill-level of labour, resource and material availability, planning permission processes, government policy and the market landscape.

For each scenario, between 3,600 and 20,000 electric depot chargers must be built per year in 2060. The main potential limitations for this are the need for network upgrades where many depot chargers are needed, and the potential competition for supply with the light duty vehicle sector.

For the ERS scenario, the peak build rate is 274 km/year in 2040, based on the trajectory of switchover to electric HDVs. This technology is at an early stage of development and technically feasible build rates, industrial capability and the ability to overcome regulatory barriers over their installation are highly uncertain. The ERS installation requires road / lane closures on major routes – as these need to be booked one year in advance, and only proportions of the road can be closed at any one time (e.g. 4km), the planning requirements for this infrastructure are far greater than the others. However, this was not a concern for stakeholders who saw no major barriers to ERS infrastructure rollout but did highlight significant practical challenges that would need to be overcome in terms of scheduling of road works and lane closures, along with infrastructure inspections.

We estimate that the Hydrogen scenario would require a peak build rate of 3,600 units/year. This is thought to be ambitious given the current roll out strategies currently taking place in Germany and California.

For all scenarios, the bulk of the public infrastructure installations are completed prior to 2060, with peak build rates during 2030-2045. This is due to the large shifts in the proportion of zero emission vehicles in fleets in this period. The depot chargers (which are needed for all scenarios, albeit in differing volumes) continue to be deployed in large numbers to the end of the simulated period (2060). As the demand for road freight is expected to grow beyond 2050, there is no specific end date of infrastructure investment for each scenario (the required amount is expected to continue increasing beyond the modelled period if demand for road freight increases).

Vehicle considerations

Both electric and hydrogen vehicles are emerging as options to de-carbonise the freight sector, with no clear preferred option for the long-haul sector at this stage. Electric charging is not thought to significantly interrupt operations of HGVs. Drivers must take a 45-minute break after no more than 4.30hrs of driving, according to EU rules (UK Gov, 2019). With sufficiently high powered ultra-rapid chargers, suited to the battery capacity of the vehicles, this is likely to provide sufficient time for recharge without affecting most operations.

Battery technologies will continue to evolve and reduce in cost due to their uptake in light duty vehicles (the rate and degree is less certain), and pantograph / catenary systems are a relatively mature, established technology. Even with these developments, it is uncertain if vehicle manufacturers can scale up manufacturing of zero emission HGVs rapidly enough to transition to a zero emission HGV fleet by around 2050. However, it is increasingly unlikely that hydrogen will provide a significant role in light duty vehicles in this timeframe, and without scale application there, technical development, cost reduction and availability are likely to be significantly slower than that for electric-dominated scenarios. Rapid growth in manufacturing and take-up of hydrogen fuel cell HGVs will be needed alongside the development of infrastructure to deliver this scenario. This is an area for further research.

Broadly, stakeholders agreed that it is important to ensure a standardised / common approach to selected technology and policy between the UK and Europe. A need for a coordination role to manage the transition was mentioned by multiple stakeholders. If this is not effectively managed, interoperability was noted as a concern, as there would be a greater need for infrastructure on both sides of the Channel to enable trailer swapping at entry points. The supporting refuelling infrastructure was noted as being of particular importance, as this may restrict (or in the worst case, prevent) the mileage achievable using zero emission powertrain HGVs in the UK or Europe.

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Glossary

Abbreviation	
BEV	Battery Electric Vehicle (fully electric)
BEV-ERS	Battery Electric Vehicle with Electric Road System (i.e. catenary or other form of dynamic charging)
ERS	Electric Road System
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle (running on hydrogen)
H2-REX	Hydrogen fuel cell vehicle with range extending diesel engine
H2-ERS	Hydrogen fuel cell vehicle with electric road system
HDV	Heavy Duty Vehicle (lorries, buses and coaches)
HEV	Hybrid Electric Vehicle
HRS	Hydrogen Refuelling Station
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
ICEV-D	Diesel ICE Vehicle
kWh	kilo-Watt-Hour
LCA	Life Cycle Assessment
LCV	Light Commercial Vehicle (van)
LDV	Light Duty Vehicle (Car or LCV)
LEV	Low Emission Vehicles (includes BEVs, PHEVs, REEVs and FCEVs)
Li-ion	Lithium Ion
LNG	Liquefied Natural Gas
MJ	Mega-Joule
Mt	Mega ton (million tonnes)
OEM	Original Equipment Manufacturer
PHEV	Plug-in Hybrid Electric Vehicle
RE	Renewable Energy
RES	Renewable Energy Sources
REEV	Range Extended Electric Vehicle
SMR	Steam Methane Reforming
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
TTW	Tank-to-wheel
TTW	Tank-to-Wheel
V2G	Vehicle-to-Grid
WTT	Well-to-Tank
WTW	Well-to-Wheel

Abbreviation	
xEV	Electric vehicles (includes BEVs, PHEVs, REEVs and FCEVs)
ZEV	Zero Emission Vehicle (includes BEV and FCEV)

1 Introduction

The Committee on Climate Change (CCC) commissioned Ricardo Energy & Environment ('Ricardo') to carry out research to assess the infrastructure requirements and costs for different zero emission HDV options up until 2050; specifically:

- Hydrogen refuelling stations (HRS) for hydrogen fuel cell vehicles;
- Ultra rapid charge points at strategic locations for battery electric vehicles;
- Electric road system (ERS) infrastructure, namely overhead catenaries for battery electric or battery hybrid vehicles;
- Hybrid solutions combining some of the elements of the infrastructure above.

The CCC was requested to advise the Department of Business, Energy & Industrial Strategy (BEIS) on setting a date for achieving net zero greenhouse gas emissions from across the economy in the context of the Paris Agreement. Achieving deep emissions reductions in the transport sector will require use of ultra low emission vehicles (ULEV), which are vehicles with zero or near-zero tailpipe emissions, which will make use of electricity or hydrogen from an increasingly decarbonised power sector. Whilst battery electric vehicles (EV) are the most promising technology for the light duty vehicle sector, the most cost-effective technology to decarbonise the heavy-duty vehicle (HDV) sector is not yet clear.

We identified a number of scenarios that were analysed with respect to the deployment of infrastructure to support different types of vehicle powertrain technologies for HDVs. These scenarios are technology-focused, and represent a push towards a certain technology type, rather than implying exclusive use of only that technology across the entire fleet of vehicles (this mostly applies to the presence of BEVs amongst smaller vehicles in all scenarios). The six scenarios are:

- Scenario 1 – Hydrogen – refuelled from hydrogen refuelling stations
- Scenario 2 – Battery electric vehicles [BEV] – charged from ultra rapid chargers
- Scenario 3 – Battery ERS – powered from pantograph and charged off motorways / A roads by ultra rapid chargers
- Scenario 4 – Hydrogen ERS [H2 ERS] – powered from pantograph and refuelled off motorways / A roads by HRS
- Scenario 5 – Hydrogen range extender [H2 REX] – on-board battery (no external charging) and hydrogen tank (refuelling from HRS).
- Scenario 6 – Plug-in hybrid electric vehicles [PHEV]. – refuelled at conventional fuelling stations and additional power from electricity.

In this report we bring together the results of the modelling of costs and requirements for infrastructure to support zero emission HDVs for each of the above scenarios. The purpose of this report is to provide estimates of the required infrastructure needed to fully de-carbonise road freight in the UK by 2050 (or as soon as feasible thereafter), and the costs of deploying this infrastructure for each of the scenarios. The report also includes results from stakeholder engagement with industry representatives. Although the focus of this work was on required infrastructure, some commentary on the feasibility of achieving zero emission HDV transport in the UK by 2050 is also provided, based on Ricardo's expert opinion and industry insight.

2 Review of available information

The Department for Transport's (DfT) Road to Zero Strategy (DfT, 2018) shows commitment to reducing emissions from heavy goods vehicles (HGV) and road freight. The road freight industry is considered a particularly difficult area of the transport sector to decarbonise, in part due to the long journey distances undertaken by some HGVs and their heavy payload requirements. Numerous zero emission solutions are being investigated for the HGV sector, but there is no current consensus with respect to which technology represents the best solution to decarbonise the sector. Additionally, there is a requirement for a substantial lead time if the industry is to be fully zero carbon by 2050 – due to aspects such as vehicle fleet turnover, infrastructure deployment and vehicle manufacturing capacity and availability, decisions need to be made within the coming years to enable the industry to adhere to any policy interventions.

This section provides a review of available information related to the infrastructure for the various zero emission powertrain technology types for HGVs considered within the current study. We begin by reviewing key literature addressing zero emission transport for the HGV sector as a whole, followed by a review of literature and information related specifically to hydrogen fuel cell HGVs, battery electric HGVs, and HGVs powered by electric road systems.

2.1 Zero emission road freight

Table 2.1 provides the list of key literature reviewed with respect to background information and previous work undertaken to address zero emission transport for the HGV sector, with key learnings from the literature also provided in the table.

Table 2.1 Summary of general literature review undertaken

Report	Key Learnings
Energy Transitions Commission (ETC) – Mission Possible (ETC, 2018)	• Significant emissions savings is available from tyre design and aerodynamics improvements. • Before 2030 much of the improvements will likely come from internal combustion engine (ICE) trucks. • Manufacturing economies of scale may tend to favour the emergence of a dominant technology for the HGV sector. • Electric drivetrains are likely to dominate in the long-term. • For long distance freight fuel cell electric vehicle (FCEV) are likely to have an advantage due to higher energy density than battery technologies and faster refuelling. • However, catenary systems could make batter electric vehicle (BEV) trucks suitable for long distance use cases.
National Infrastructure Commission (NIC) – Future of Freight (NIC, 2018)	• The UK has one of the most efficient freight systems in the world.1.6bn tonnes of freight are moved each year. • HGVs and LGVs contribute 31% of NOx emissions from transport (despite being only 21% of traffic). • Detailed freight data is not usually available to policy makers.
International Energy Agency (IEA) – The Future of Trucks (IEA, 2017a)	• Further policy measures are needed to stop oil demand from road freight reaching 5 mb/d by 2050. • Road freight is expected to rise by a factor of 2.4 by 2050 in the baseline scenario.

Report	Key Learnings
	• The modern truck scenario sets out an achievable, but ambitious decarbonisation pathway. Includes a 13% efficiency improvement in freight operations, a 34% reduction in carbon intensity of vehicles (from alternative fuels and electrification) leading to a CO_2 emissions reduction of 75% by 2050. • This pathway could be achieved through tightening of fuel efficiency standards, capitalising on digital technology advances, R&D, improvement of charging or alternative refuelling infrastructure.
European Climate Foundation (ECF) – Trucking into a Greener Future: the economic impact of decarbonizing goods vehicles in Europe (ECF, 2018)	• All scenarios for low carbon road freight require a joined approach from government, industry and civil society. • HRS and electric charging infrastructure will cost several billion euros per year from 2030 to 2050. • BEVs and ERS vehicles achieve lower total cost of ownership and FCEVs achieve parity when compared to diesel HGVs.
Julich – Comparative Analysis of Infrastructures: Hydrogen Fuelling and Electric Charging of Vehicles (Julich, 2018)	• Infrastructure costs are dependent on the uptake levels of the technology. For low uptake scenarios, hydrogen and electric infrastructure costs are equal, then in the transition phase (1-10m EVs), electric infrastructure is cheaper, and at very high uptake levels (>10m EVs), hydrogen becomes cheaper. • This study includes the cost of electricity/hydrogen generation. The lower cost of hydrogen infrastructure arises from lower necessary build of renewable energy due to flexible hydrogen production from excess electricity.

2.2 Technology focus – hydrogen fuel cell HGVs

2.2.1 Hydrogen refuelling stations

Hydrogen refuelling stations (HRS) are the key infrastructure component of the roll-out of FCEVs. The deployment of these stations has been growing recently in the UK and there are now 15 installed throughout the country. A second wave of funding for 5 further projects has recently been announced as part of the second phase of the Hydrogen Transport Programme (Hydrogen Transport Programme, 2019).

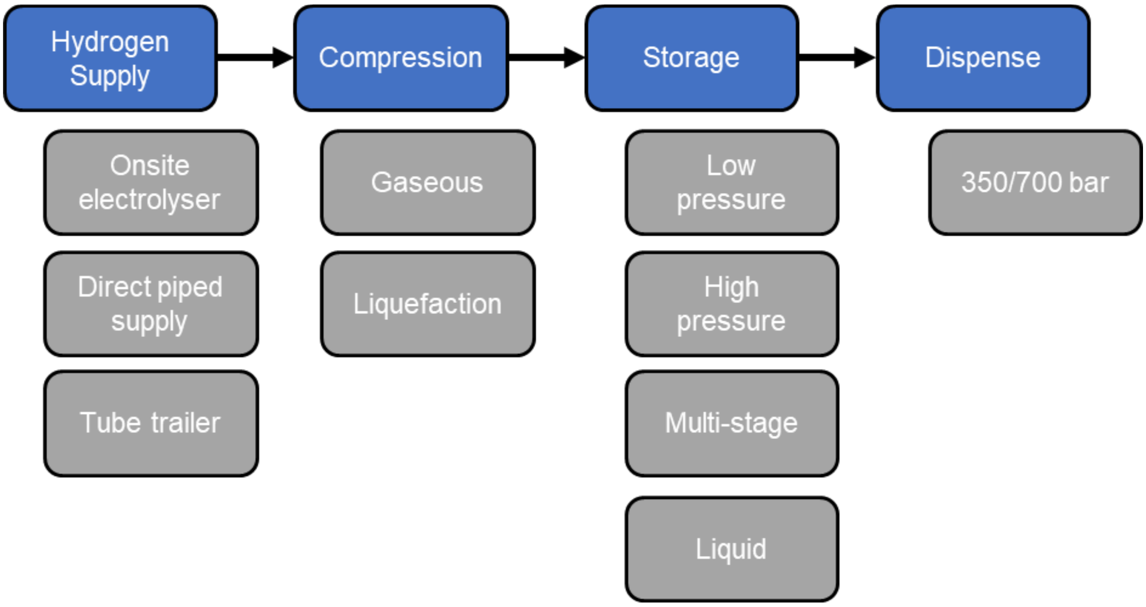
The current crop of HRSs in the UK are installed in a range of locations as shown in Table 2.2. 40% of the locations are close to motorways and therefore the location would be suitable for supporting hydrogen HGVs. Each of these stations has one dispenser, and as such only one vehicle can refuel at any given moment.

Table 2.2 Location types for currently installed HRS in the UK

Location Type	No. UK HRS
Motorway	6
Urban	6
Airport	1
Industrial park	1
University	1

The key components of an HRS are shown in Figure 2.1. For higher capacity stations, the storage capacity must be increased; however, there may not be a need to increase the number, or capacity, of the compressors and dispensers. It is thought that the operation of HRSs for HGVs is unlikely to change with the required increase in capacity.

Figure 2.1 HRS components and schematic flow of hydrogen through the station



Capacity of HRSs is generally denoted in kgH2/day. It is anticipated that, in the 'Hydrogen' scenario, a small HRS would have a capacity of 200-400 kgH2/day, and a medium sized HRS would have a capacity of 800-1200 kgH2/day. Within our study, we do not make an estimation with respect to the number of dispensers at each station, as this is likely to be specified on an HRS by HRS basis, based on the expected demand patterns of the stations. The most important parameter is the capacity to deliver a certain amount of hydrogen per day.

2.2.2 Market review of hydrogen fuel cell HGVs

The market for FCEVs is in its infancy; with only a handful of vehicles currently announced, the breakdown of currently announced vehicles is shown in Table 2.3. Of particular note is the high proportion of range extended (RE) FCEVs. This drivetrain type has not yet emerged to be specifically useful for a single use case, and as such different vehicle types are employing it. The Plug Power & Workhorse vehicle was designed for Fed-Ex as an urban delivery vehicle and therefore has a relatively short range of 160 miles. However, the Nikola trucks are designed for long distance haulage with large batteries and very high range capability, in the region of 500-1,000 miles.

Of the pure hydrogen HGVs there is more certainty, with both HGVs analysed being medium range HGVs, as shown in Table 2.3, with a range of 200-300 miles.

Table 2.3 Currently announced hydrogen fuel cell HGVs.

Manufacturer/Model	Range (miles)	Hydrogen Capacity (kg)	Battery capacity (kWh)	Size	Source
Range Extended FCEV					
Nikola One	500-1000	100	240-1000	Artic (US)	(Nikola, 2019)
Nikola Two	500-1000	-	240-1000	Artic (US)	(Nikola, 2019)
Nikola TRE	500-1200	-	240-1000	Artic (Europe)	(Nikola, 2019)
Plug Power & Workhorse	160	11.6	80	Small Rigid	(Ayre, 2018)
Pure Hydrogen FCEV					
Kenworth Truck Company and Toyota Motor T680s	300	60	12	Artic (US)	(Green Car Congress, 2019)
Hyundai	238	32.86	-	Large Rigid	(Turpen, 2018)

***Hyphens indicate that info is unavailable.**

2.2.3 Key literature reviewed – hydrogen infrastructure

Table 2.4 provides a list of key literature reviewed in gathering information for hydrogen refuelling infrastructure.

Table 2.4 Key literature reviewed for hydrogen refuelling infrastructure and associated learnings

Report	Key Learnings
CCC – Hydrogen in a Low-Carbon Economy (CCC, 2018)	• Decisions must be made in the 2020s regarding infrastructure provision for zero carbon HGVs. • There are unanswered questions on the supply mechanism of hydrogen for future mobility regarding the suitability of the gas grid and the purity of hydrogen. These unknowns are largely dependent on other industries. • Hydrogen fuel cells, battery technologies and electric road systems are competing technologies for powering future HGVs with zero carbon emissions.
OLEV – Fuel cell electric vehicle fleet support scheme (OLEV, 2016)	• £2m funding announced to support fleets of FCEVs (cars only). • This funding aims to increase public awareness and knowledge of the technology.
UK H2 Mobility – Communication Pack (UK H2 Mobility, 2017)	• Joint industry-government project to assess the benefits and plan the roll out of hydrogen transport technologies.

Report	Key Learnings
	• Switching from imported fuels to domestically produced hydrogen could deliver a benefit of 1.3bn GBP/year by 2030 across the whole transport system. • Roll out should be based on a network of clusters which are subsequently joined to form a national network.
Shell – Hydrogen Study Energy of the Future? (Shell, 2017)	• Fuel cell electric HGVs are currently at technology readiness level (TRL) [4] 6-7 with well-developed prototypes and initial products coming to the market. • Minimising losses of payload and competitive fuel prices are prerequisites for adoption of FCE HGVs. • Current hydrogen storage system energy density by weight is 6MJ/kg with a medium to long term target of 9MJ/kg.
ICCT – Hydrogen Infrastructure Status (ICCT, 2017a)	• It is still far cheaper to produce hydrogen from fossil fuels than from renewable energy. • Toyota dominates the market for FCEVs with the Mirai passenger vehicle accounting for 75% of total vehicle sales. 48% of all FCEVs are sold in California. • Hydrogen production costs vary with process and scale. Retail prices are expected to fall to $4-6/kg by 2025. • HRSs should be developed with clusters of multiple stations servicing local demand, then these clusters should be connected with corridor HRSs.
NREL – Hydrogen Station Cost Estimates (NREL, 2013)	• Capital cost per installed capacity is likely to fall to $3,000/kgH2/day by 2030.
LowCVP Report – Transport Infrastructure Roadmap to 2050 (LowCVP, 2015)	• Future HRSs are likely to be integrated with existing petrol stations. • Beyond 2025, all HRS capacities will be above 500kg/day due to economies of scale. • Predicted roll-out of infrastructure: >300 HRSs in the UK by 2025 and >1,000 by 2030.
FCH JU - Development of Business Cases for Fuel Cells and Hydrogen Applications for Regions and Cities (FCH JU, 2017)	• Fuel cell electric HGVs are currently at TRL 6 with well-developed prototypes and initial products coming to the market. • HRS availability is key for long distance inter-regional routes (>500km).
California Environmental Protection Agency – Technology assessment:	• Early market for HGVs in operations where vehicles are fuelled, operated and maintained centrally. • Most of California's HRS are located at fuel stations.

[4] The TRL is a means for indicating the maturity of a given technology. It runs on a scale from 1 to *9*, with *9* being the most mature technology A TRL of 1 indicates the basic principles of a technology have been observed, and 9 indicates the system has been proven in an operational environment.

Report	Key Learnings
Medium- and heavy-duty fuel cell electric vehicles (EPA, 2015)	• Medium and Heavy-Duty Vehicle refuelling should be developed into a standard by SAE. • Financial and regulatory approaches should be used to transition to FCEVs.

2.3 Technology focus – battery electric HGVs

2.3.1 Charging infrastructure for battery electric HGVs

Due to the expected size of the batteries in HGVs, the vehicles are likely to have a charging rate requirement far in excess of the capability of the current charging infrastructure and will require substantial grid infrastructure reinforcement. However, except for the Tesla Semi, all the currently announced electric HGVs are charged using existing charging protocols. These have the following limits:

- CHAdeMO – Up to 150kW DC (@400V and 375A) (and potentially up to 400kW with CHAdeMO 2.0)
- CCS – Up to 150kW DC (new charging infrastructure aims to provide charge at 800V and could go up to 350kW DC, e.g. Ionity).

It is currently unclear whether a new industry standard will be developed specifically for HGVs to allow for short duration charging of very large capacity batteries. Tesla have progressed with this, and have developed a Tesla Semi charger which, anecdotally, is capable of charging power up to 1.6MW (Clean Technica, 2017). This is clearly significantly higher than any current alternatives. It seems likely that, using new 800V charging technology, power levels of at least 350kW are feasible and potentially much higher for even higher voltages and currents. This would likely require specific infrastructure for HGVs because passenger cars are unlikely to need this level of charging.

There are currently over 2,000 rapid charger devices in the UK (as of March 2019) (ZapMap, 2019). These rapid chargers would not, for the most part, be suitable for HGVs due to the larger batteries within HGVs and as such, higher power requirement for rapid charging of HGVs. Furthermore, from a practicality perspective, most of these chargers would not be accessible by HGVs due to locations and parking bay sizes. However, the number of installations in the UK to-date demonstrates the capability of the industry for a relatively rapid roll-out of chargers when supported with government funding. It should also be noted that most rapid chargers to date have been placed in locations where grid reinforcement can be avoided – this speed of deployment may not be possible with infrastructure that requires an order of magnitude higher power and potential grid reinforcements.

There is currently a trend for rapid chargers to achieve higher powers than those currently installed. 150kW chargers are currently being offered by some rapid charger installers in the UK. The European mainland charger network is ahead in this regard with 350kW chargers currently being rolled out by Ionity (Ionity, 2019). This type of roll-out is being discussed in the UK with 50 strategic locations identified for installations of 350kW chargers, this is intended to provide coverage for all of England and Wales, with locations chosen with proximity to an appropriate grid connection in mind (National Grid, 2019).

It is clear though, that the majority of charging installations in the UK to date are to support electrification of the light duty fleet. A network for HGVs would need to have higher power capacities due to the larger battery capacities expected amongst a fleet of electric HGVs. However, there is not yet any clarity over the standards which would govern a higher power charger network for trucks.

2.3.2 Market review of battery electric HGVs

The electrification of HGVs is a process which is already underway. The HGVs that have currently been announced are detailed in Table 2.5. This shows the polarised nature of the market currently. Most producers are aiming the HGVs at the city distribution market (due to air quality concerns being more prevalent here) and as such, range and battery capacities can be low as the overall mileage for vehicles used in this way is low. The Tesla Semi, however, is not aimed at this market, and is instead aimed at long distance haulage. The range of this vehicle is therefore much higher.

Table 2.5 Currently announced electric HGVs

Manufacturer / Model	Vehicle Class	Battery Capacity (kWh)	Range (miles)	Citation
BEVs				
Tesla Semi	Artic	1000*	300-500	(Tesla, 2018)
Renault Trucks	Common base platform shared amongst models 16 – 26 tonne	300	190	(Renault Trucks, 2018)
Mercedes-Benz Electric Truck	26t Large Rigid	200	124	(Daimler, 2019)
BYD T5	Small Rigid	145	155 (half-load)	(BYD , 2019)
BYD T7	Large Rigid	221	124 (full load)	(BYD , 2019)
BYD T9	Artic	435	124 (full load) / 167 (half-load)	(BYD , 2019)
Volvo FL Electric	Small Rigid	100-300	Up to 186	(Volvo Group, 2018a)
Volvo FE Electric	Large Rigid	200-300	124	(Volvo Group, 2018b)
VW e-Delivery	Small Rigid	-	124	(Volkswagen, 2018)
Peterbilt 220EV	Small Rigid	148	100	(Peterbilt, 2019)
Peterbilt 579EV	Artic	350-440	150-250	(Fleet Equipment Mag, 2018)
Arrival Royal Mail/UPS	Small Rigid	-	100-150	(Arrival, 2019)
D-REEVs				
Tevva Motors ReX	Small Rigid	-	100 electric, 250 total	(Tevva, 2019)
Calor/EMOSS	Small Rigid	-	40 electric, 250 total	(SMMT, 2017)

Notes: (* calculated based on range and assumptions); Hyphens indicate that no information is available

2.3.3 Key literature reviewed – charging infrastructure for battery electric HGVs

Table 2.6 provides a list of key literature reviewed that pertains to the information gathering specifically for charging infrastructure for battery electric HGVs.

Table 2.6 Key literature reviewed for charging infrastructure and associated learnings

Report	Key Learnings
European Federation for Transport and Environment – Analysis of long-haul battery electric trucks in EU (T&E, 2018)	• A European fleet of battery electric trucks could require up to 10% of current electricity generation • The biggest sensitivity to cost competitiveness is the electricity price • The total cost of ownership for a BEV HGV is dependent on the battery size, due to the high cost associated with battery technology
Bain – How Europe's Truck Makers Can Break Out of the Pack (Bain, 2018)	• Total cost of ownership is a key criterion for purchase decisions of truck buyers in Europe. • In medium- and long-term truck makers will need to meet demand for alternative drivetrains. • 40% of truck buyers may want to buy an electric or electric hybrid truck as their next purchase. • Only 30% of truck buyers believe diesel will be the main drivetrain in their fleet by 2025.
ACEA – Alternatively-powered trucks Availability of truck-specific charging and refuelling infrastructure in the EU (ACEA, 2019)	• Infrastructure for truck-specific charging is not available today. • Heavy duty trucks cannot use the same charging infrastructure as cars. • Standards for truck charging do not yet exist. • 6,000 rapid (>500kW) chargers are needed across Europe by 2030.
McKinsey Energy Insights – New reality: electric trucks and their implications on energy demand (McKinsey, 2017)	• Electric truck market share could reach 15% by 2030. • Cost parity with diesel is expected for most segments by 2025. • Supply of trucks and infrastructure is unlikely to meet demand in the short term.

2.4 Technology focus – electric road system HGVs

DfT aim to investigate zero emission road freight options, as set out in the Road to Zero Strategy. The UK government announced a research project to "explore different zero emission HGV technologies, including dynamic charging which involves vehicles receiving electricity as they travel". The strategy also states that "Manufacturers have produced large electric HGVs and there has been several successful trials of dynamic charging technologies for HGVs internationally." (DfT, 2018).

Whilst there are numerous types of ERS systems that can serve HGVs, it is important to note that **overhead catenary systems comprise the focus of our analysis** – in consultation with the CCC, it was decided that overhead catenary systems represent the most promising and cost-effective solution for ERS infrastructure supporting HGVs. This section begins by briefly describing the different types of ERS infrastructure that currently exist, followed by focusing solely on overhead catenary systems.

2.4.1 Types of electric road systems for HGVs

There are three primary solutions that are theoretically possible with respect to electric road systems for HGVs, which are as follows:

a) Overhead conductive technology (catenary system) – catenaries hanging over a lane of a road and connects to HGVs via a pantograph installed on the HGV;
b) Dynamic on-road conductive technology (CPT) – contact rail is built into road's surface, providing power via physical pick-up;
c) Inductive power transfer (IPT) – wireless power transfer from coils built into the road to a pick-up point in the vehicle.

Overhead conductive technology – catenary systems

These systems involve hanging catenaries over a lane of a highway from road-side gantries or other infrastructure and connecting to an HGV via a pantograph installed on the HGV, with power transfer between the catenaries and the HGVs. Substations are installed along the highway to power the infrastructure. With respect to experience and maturity of the infrastructure, Siemens Mobility owns a test facility, and there are demonstration projects ongoing in the USA and field trials in Germany and Sweden (ELISA, 2019) (FESH, 2019) (Gavle, 2019), all of which are on public roads.

The focus for overhead catenaries is on short, repetitive journeys and long-haul operations. With respect to advantages of the system, high efficiencies have been reported (77% well-to-wheel) when compared with other alternative propulsion systems, leading to low OPEX for users. Many existing relevant electrical industry standards can be adopted for overhead catenary systems, and no alteration is required of the existing road structure. There is minimum disruption during installation and maintenance works when compared to other technologies, and the infrastructure has a strong safety record, with a proven electrical safety concept (based on tram and rail applications). In terms of drawbacks, the catenary infrastructure is not suitable for passenger vehicles due to their lower height; however, investments into power supply infrastructure (substations and transmission grid) could be shared for both passenger vehicles and HGVs (e.g. for deployment of nearby EV charging points). The catenary system does require a considerable amount of infrastructure to be deployed along long stretches of roads which can be perceived as unsightly.

Dynamic on-road conductive technology (CPT)

Similar to overhead catenaries, substations are needed alongside the highway to power the infrastructure, but implementation is carried out inside the road rather than via a mast / catenary system. These systems have been installed and tested on test tracks and public roads by manufacturers such as Elways (for their eRoadArlanda project in Sweden (STA, 2019)) and Alstom APS (based on a tram system that is currently in used across numerous cities). The system consists of sections of conductive rails imbedded in the road surface that deliver power to the vehicles via a current collector on each vehicle. Each section of the rail is energised only while the vehicle is over it. One primary advantage of this system is that it could be used by both passenger vehicles and HGVs. It also avoids having to deploy extensive above ground infrastructure. Very little information on costs is currently available. One of the major concerns with such systems is about having infrastructure installed within the road's surface or inside its inner structure, which could lead to extensive road works required and potential maintenance issues.

Inductive power transfer (IPT)

This involves the wireless transfer of energy to power vehicles whilst they are in motion on a highway. Similar to the previous two examples presented above, substations are installed alongside the highway to power the infrastructure. These systems have been installed and tested primarily on test tracks, and on one public road (for a trial for public buses in South Korea (GCC, 2013)) – examples of manufacturers and projects include Bombardier primove in Germany (Bombardier, 2019), the FABRIC project in Italy (FABRIC, 2019); and the ELinGO project in Norway (ELinGO, 2019), with additional information provided in a Highways England study (2015). This system could be used by both passenger vehicles and HGVs (although it is uncertain whether the same infrastructure can provide adequate levels of efficiency and safety at two different power levels for light duty and heavy-duty vehicles) and has no visible infrastructure. However, similar to the CPT, the infrastructure requires extensive adaptation of the road structure, requiring extensive road works and posing potential road maintenance issues. Additionally, magnetic field exposure could present a concern for some users (e.g. those with heart pace makers) and there could be issues with EMC for non-equipped vehicles. High costs of this technology and required road adaptation have also been cited as a potential barrier.

2.4.2 Market review of pantograph HGVs

Table 2.7 displays a market review of HGVs equipped with a pantograph to connect to overhead catenary systems, with all vehicles currently in trial mode. None of these have been announced as being manufactured in high volumes; but several HGV OEMs are actively developing plans to manufacture pantograph HGVs, including Scania and Volkswagen.

Table 2.7 Pantograph electric HGVs currently being trialled

Base Vehicle	Modified by	Drivetrain	Electric drive power (kW)	Energy storage capacity (kWh)
Mack Pinnacle	Volvo Group	Hybrid	120	1.2
Navistar International Prostar	Transportation Power Inc.	Hybrid	300	115
Navistar International Prostar	Transportation Power Inc.	BEV	300	115
Scania S-series	Siemens / Scania	Hybrid	-	15

2.4.3 Key literature reviewed – overhead catenaries for HGVs

We carried out a review of literature related to overhead catenary systems for HGVs. As ERS is a relatively new concept, literature available on this topic is more limited than for the other technologies. Therefore, this literature review is structured differently than the previous two sections – the information from the literature review is divided into subsections based on the subject topic being analysed.

Costs of overhead catenary infrastructure

One study (Fraunhofer IML, 2017) assess two variants:

1. Catenary infrastructure for trucks equipped with diesel and smaller battery
2. Catenary infrastructure for trucks equipped with diesel and battery > 150kWh.

Infrastructure costs are distinguished between "starting phase / partial ERS network" and "completion phase – full network", and best- and worst-case scenario. The figures in EUR "per km" are stated as "per double km", i.e. per kilometre in both directions. Three main questions are essential for the costs:

1. Distance from motorway and substation to the next power-infeed-point – if it is close to the motorway, it's easy and cheap;
2. The number of trucks to be supplied with electrical energy and required distance between trucks whilst driving (this can be compared with electrical railway and metro systems). If there is a traffic jam, there should not be problems as the trucks are starting one after another in one feeding section (i.e. the section of the catenary that is electrically separated from adjacent sections – there is a limit to how much power can be supplied via each section);
3. Topography of the motorway (slopes, tunnels, etc.).

With respect to the costs per component, Fraunhofer IML (2017) estimated the costs of components based on long-term experiences in the railway industry:

a) Substation: EUR 300,000/km in both directions (based on the assumption 3 MVA is needed every 3km for both directions), as the substation feeds both lanes;

- In both German field trials, they have two substations of around 1 MVA each supplying power for 5+5 = 10km.

b) Masts: EUR 10,000 per mast (based on the assumption of one mast every 50m on 2km distance (each lane) = 40 masts x EUR 10,000 EUR/mast which makes it EUR 400,000/km in both directions for the German field trials.
c) Catenary wire: EUR 300,000/km, and EUR 600,000/km in both directions.
d) Connecting to in-feed point: EUR 5,000/km
e) Cabling to substation: EUR 25,000/km
TOTAL: EUR 1,330,000.

Another study (Oeko Institute, 2018) estimates the minimum infrastructure requirement and associated costs for overhead catenary infrastructure, based on the configuration of the system (i.e. how many HGVs can be supported by the system). Table 2.8 below contains information on the differences in the configurations of the system, with the investment costs per kilometer also displays in the table.

Table 2.8 Minimum infrastructure requirements for different overhead catenary system configurations [Source: (Oeko Institute, 2018)]

Category	Base configuration	Performance system	High performance system
Installed continuous power per km and direction:	500 kW / km	1 MW / km	1.5 – 2 MW / km
Installed substation continuous power:	500 kW / km	1 MW / km	1.5 – 2 MW / km
Distance between substations:	3 km	1.5 km	1 – 1.5 km
System voltage (nominal voltage)	750V DC	750V DC	750 – 1,500V DC
Number of vehicles per km (max number permitted)	4	8	12-16
Number of vehicles per km and direction (incl. battery recharge)	2	4	6-8
Vehicle cycle per direction (power consumption of 180kW)	16s	8s	5.4-4s
Investment costs per kilometre (**both directions**)	€1.7m/km	€2.6m/km	€2.9-3.1m/km
Investment costs per MW (**both directions**)	€1.7m/MW	€1.3m/MW	€0.77-0.96m/MW

Another study (ECF, 2018), using a calculation from Umweltbundesamt (2016), uses a calculation which concludes installation costs of EUR 2.43million/km (double km) in 2020 and EUR 2.02million/km (double km) in 2050. 'Installation' is to be understood to include all infrastructure elements necessary (from substation to overhead wires).

For maintenance costs, a study by Oeko Institute (2018) states that maintenance is calculated on a timely basis, rather than per kilometre, and is calculated as 2% of the infrastructure costs per annum.

Lifetime of overhead catenary infrastructure and rate of replacement

The Fraunhofer IML study (2017) estimates the lifetimes of components based on long-term experiences in the railway industry:

- Pantograph on the truck: **6 years**
- Transformers and rectifiers inside substation: **30 years**
- Medium voltage switchgear inside substation: **40 years**
- Masts: **40 years**
- Catenary wire: **7 years** on German motorways (depending on usage intensity / number of trucks)
- Other catenary components: 20 years

Financing options for infrastructure

Using Germany as an example, the Oeko Institute (2018) study shows a simple graphic comparing the infrastructure costs of an eHighway system in its different phases (starting, expanding and completion) to the earnings received from HGV tolling and other essential investments in national infrastructure (broadband and renewables) made in recent years or to be spent. Germany earns EUR 5 billion every year for their HGV tolling (which is used to maintain roads). The German financial newspaper handelsblatt.com reported that an increase to 7.2 billion EUR can be expected in the next years (Handelsblatt, 2019). From a calculation undertaken by Siemens, this estimates that 4,000km of Siemens eHighway could be financed by that tolling fee in less than 2 years if tolling fees are raised by 11%.

Maximum number of kilometres of ERS infrastructure that can realistically be installed

Referring to Germany and its 12,000km motorway network, there have been various studies published in recent years examining maximum expansion level of ERS (based on either maximum amount that can be deployed, or maximum that should be deployed to achieve policy goals (such as (BDI, 2018))) which may be applicable to the UK, as shown in Table 2.9 below:

Table 2.9 Maximum kilometres of ERS infrastructure that can be installed in Germany

Maximum kilometres constructed	Source
4,000 – 8,000 km by 2050	(BDI, 2018) pg. 183 & 185
2,000 – 2,500 km by 2030	(Fraunhofer IML, 2017) pg. 7, 149, 195
4,000 – 6,000 km by 2050	(Fraunhofer IML, 2017) pg. 7 & 170
8,000 km by 2050	(Renewbility, 2016) pg. 22 & 23
4,000 km by 2050	(Umweltbundesamt, 2016) pg. 31 & 52
5,700 km by 2050	(SRU, 2012) pg. 239
10,400 km by 2050	(IFEU, 2015) pg. 69

There are additional views for maximum number of kilometres of ERS infrastructure based on Europe and the world in total, again based on either maximum amount that could be deployed or the quantity that should be deployed to achieve policy goals, as shown in Table 2.10.

Table 2.10 Maximum kilometres of ERS infrastructure that can be installed in Europe and World

Region	Maximum kilometres constructed	Source
Europe	>25,000 km in 2050	(IRU CVOF, 2017) pg. 28
World	“Large Number” of km	(IEA, 2017b) pg. 65 & 72
World	630,000 km	(Singh, 2016)

Evolution of vehicle pantograph cost

A study by the ICCT (2017b) estimated cost developments for the pantograph system on the vehicle, which are as follows:

- 2015: USD 71,700
- 2020: USD 49,600 (31% improvement compared to 2015)
- 2025: USD 21,200 (=71% improvement compared to 2015)
- 2030: USD 21,200

Another study (ECF, 2018) arrived at different cost estimates, estimating a cost of EUR 17,000 in 2015, and EUR 11,000 in 2025, as they approach market maturity.

3 Stakeholder engagement

In order to develop a broader understanding of the infrastructure costs and requirements for various zero emission HGV powertrains, we undertook extensive engagement with industry stakeholders and experts. The aim of the engagement was to:

- Fill knowledge / information gaps following literature review;
- Verify operational considerations (especially for road and vehicle operations);
- Potential future technology developments and cost reductions.

We identified stakeholders and individuals within organisations that could contribute to our study and carried out structured interviews with these stakeholders based on a predefined list of subject topic areas. The interviews were structured in order to address known gaps in knowledge. The stakeholders were divided into various categories based on their areas of expertise – using a list agreed in advance with the CCC, Table 3.1 presents the list of stakeholders that responded to requests for interviews:

Table 3.1 List of stakeholders that responded to requests for interviews

Stakeholder Type	Stakeholder Name
Road freight operators	Freight Transport Association (FTA)
	Road Haulage Association (RHA)
Road owners / operators	Egis
	Connect Plus Services
Infrastructure suppliers / manufacturers	ITM Power [H2]
	Siemens [ERS]
	Shell [H2]
	Shell [BEV]
	BP Chargemaster [BEV] (provided information via email)
Current infrastructure operators	German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMUB)
	Hesse (road operator; provided information via email)
	FH Kiel GmbH (research institution; provided information via email)
	Oeko Institute (research institution; provided information via email)
	Institute for Energy & Environmental Research (IFEU – Germany) (provided information via email)

During the project, we attempted to contact additional stakeholders – Highways England, Tesla and ABB – but have received no responses from them. The main high-level outcomes of our stakeholder engagement are presented in the sub-sections below, divided into the category of stakeholder being considered. Detailed findings from the stakeholder engagement activity are available in Appendix 1. Summaries provided below are paraphrasing stakeholder and expert feedback and comments. Ricardo's own comments are indicated via "**Ricardo Comment**".

3.1 Infrastructure suppliers / manufacturers

3.1.1 Hydrogen refuelling stations

The views in this section were mainly provided by Shell; with some supporting information provided by ITM Power (whose focus is on electrolysis and as such was not of specific relevance to this study).

Capital costs of hydrogen refuelling stations

- Government intervention is required for subsidies over a fixed period of time – costs are far higher than traditional refuelling stations.
- The major parts of the capital cost breakdown for HRSs are storage, compression and dispensing. Storage and compression are the costs that need to come down.
- The upskilling of the workforce is expected to be a major cost to roll out the infrastructure. Big market players are currently doing the installations; there is a need to upskill the workforce, which would be the main installation cost.

Operational costs of hydrogen refuelling stations

- The operational costs can be considered to be the same as a conventional refuelling site. Once the HRS is in the ground and in operation, the software is the same as a normal retail site and it has the same payment mechanism; gas rather than liquid, but similar costs.

Evolution of costs and future reduction potential

- The consensus of the hydrogen industry is that if the capital costs of the infrastructure are not at cost parity with traditional refuelling by 2030, then the technology may not be viable. 2050 was noted as being too long of a time frame to get to cost parity, and hence 2030 is the aim.
- Two primary uncertainties: hardware, and policy for regulating electricity needed for hydrogen production (if assuming the main method of production will be electrolysis;
    - **Ricardo comment**: typically, SMR with CCS is assumed to be the most cost-effective method).

Lifetime / incentives for hydrogen refuelling stations

- The lifetime of an HRS can be considered to be the same as a conventional site – they are refreshed every 10 years. All sites are using conventional sites as benchmarks.
- The initial deployment of HRSs depends on policy makers – a good incentivisation policy can enable the market pretty quickly.

Challenges around deploying and operating hydrogen refuelling stations

- The longest lead time is the planning and permitting process. Doing a lot of work upfront is usually beneficial – e.g. engaging authorities long before the planning application goes in.
- There shouldn't be any supply chain issues for HRSs.

Minimum power requirements for hydrogen refuelling stations

- The minimum power requirement depends on the source of hydrogen – for an electrolyser site of 200kg per day, a 1MW power source is required. This increase linearly – 10MW would be required for an electrolysis station producing 10x the hydrogen.
- Tube trailers require a small power upgrade for compression and dispensing, but not much more than a standard retail site. A rough estimate is 50% extra power on top of a standard retail site.

Refuelling capacities & behaviours at hydrogen refuelling stations

- The number of HGVs that can be supported by an HRS is linked to demand. If every truck going through is filled once per day, they're likely taking 8-10kg of hydrogen per fill. As such, 100 trucks would consume 1 tonne per day, which would be a sizable station.
    - **Ricardo comment**: this view appears based on existing vehicles sizes and refuelling habits, where the tanks are smaller, and drivers are not fully refuelling their vehicles. The vehicle sizes within the current study are far in excess of the 10kg of refuelling stated here.
- For number of dispensers, 100 trucks per day would require 4-6 dispensers; the question becomes whether there would be redundancy on the compression. The limiting factor is the ability to store and produce hydrogen at a particular site, which limits the amount of trucks that can be serviced.
    - **Ricardo comment**: the hydrogen production mentioned here is also specific to electrolysis.

Infrastructure build rate limitations

- Build rate limitations are more about skills than the time taken to construct. The complete construction time is 12-18 months, which does not include the planning and permitting process, which comprises the frontloading that takes more time. Total time: 3 months permits; 6-9 months constructing; 6-9 months civil engineering.
- Skills and upskilling of the workforce can be considered the main limiting factors.
    - **Ricardo comment**: the H2 Mobility Germany project (H2 Live, 2019) has incorporated a build rate model seeking to deploy 400 HRS sites between now and 2023, showing the scale that can be achieved in a short space of time.

Additional considerations

- Infrastructure operators are committed to commercialising hydrogen, but they state that they need a policy that helps this happen. They would like to see incentives in place that are time-based. Infrastructure operators would like to talk to policy makers about this – they think a different approach to incentivising is required.
    - **Ricardo comment**: stakeholders did not specify how they would like the incentives to be time-based, or how this differs from current incentivisation policies.

3.1.2 Charging infrastructure

The views in this section were mainly provided by Shell; with some supporting information provided by BP Chargemaster and Tesla via email.

Capital costs of ultra rapid charging infrastructure

- Capital costs of ultra rapid charge points are commercially sensitive. However, a significant proportion of the total cost goes towards power supply upgrades / reinforcement.
- For 150kW charge points, DNOs have to build new substations. This could cost in the region of £100k. However, this varies by location and there is not a linear relationship between charger power and upgrade cost.
- 350kW charge points are not common yet – IONITY (the joint venture being led by German car manufacturers) are seeking to roll out 350kW charge points in the UK; however, there is no visibility on CAPEX costs.
- The main components of the capital costs can be considered to be the hardware, DNO connection, power upgrade, and commissioning.
- The hardware costs of infrastructure can be considered to be a roughly linear relationship – i.e. cost of hardware for 150kW = 3x cost of hardware of a 50kW [two stakeholders supported this assumed relationship].

Charging infrastructure requirements

- Infrastructure suppliers are keen to ensure all customers can use the infrastructure with respect to charge point connections – preference shown for making them downwards compatible.
- Infrastructure operators plan to react to the market and to customer demand in their assessment of whether ultra rapid charge points will be necessary,

Charging infrastructure build rate limitations

- 150kW charge points would take one week to install, on the premise that the infrastructure is already in place (such as power upgrades & DNO connections). 350kW charge points take slightly longer to install – a few weeks rather than one week.
- It takes 6 months plus, on average, for the DNO upgrade to be in place – this includes civil costs (i.e. ground works, re-cabling, etc., which are not considered to be too onerous). Depending on the size of the charge point, planning permission may be required, which also involves a 12-week lead time.
- The hardware for ultra rapid charge points are on a 6-8 week lead time, depending on the supplier and the requirement for the infrastructure.

Limiting factors to deployment of ultra rapid charge points

- Local authorities approving planning permissions and DNO upgrades can take months (estimated at 3-6 months, though estimations vary) and cause delay.
- One stakeholder noted that the challenge of installing ultra rapid chargers rises with size of installation primarily due to the cost of the grid connection. From their experience of rolling out a network of higher-powered charge points, the need to get permission (known as a wayleave) to lay cables across third party land is considered a major barrier (the wayleave is between the DNO and the land owner). It can delay projects for months or even over a year with no clear process or timelines. This applies any time chargers are being installed above the available power level at a given site and the cabling is required to go through third-party land. This is a major barrier to rollout of multiple ultra rapid chargers in the UK.
- The difficulties of wayleaves are also almost unique to the UK, which is considered by some suppliers to be one of the most difficult places to roll out charging infrastructure.

3.1.3 Overhead catenary infrastructure

The views in this section were mainly provided by Siemens; some of the information was provided from research institutions via Siemens.

Costs of ERS infrastructure

- The cost of the eHighways system funded by the Federal Ministry for the Environment, nature Conservation and Nuclear Safety in Germany is €14.6m for 5km in each direction = 10km in total; this includes customer's project management costs.

Financing for ERS infrastructure

- Public financing for a period up to 30 years may allow interest rates below 2%. Private financing is often linked to a 10-year period – higher interest rates due to credit worthiness and higher expectation of incoming cash flows.

Construction time per kilometre of ERS infrastructure

- 1 month / single km was achieved in both German field trials, which can be significantly accelerated by deploying extra construction personnel (e.g. two-shift-operation and more teams working at the same time).
- Basic factors affecting construction time include:
  - conditions e.g. topography and traffic density of respective motorway;
  - regulations set by motorway operator (blocking times e.g. holiday season, night work bans, setting-up construction site e.g. temporary or permanent);
  - allowed length of construction site / limited access ways to construction site due to structures alongside the lanes e.g. noise barriers;
  - availability of trained installation personnel and special vehicles (for pulling the contact wire, telescopic crane for deploying the substations).
- For both German field trials, the time span from site identification to delivery was:
  - 6 months site identification
  - 6 months tendering (2 step-approach)
  - 9 months construction (incl. engineering and civil works)
  - 3 months commissioning.

Ownership of ERS infrastructure

This depends on a political decision how motorways today and in future are intended to be managed:

1. Motorway operators, private- or state-owned (e.g. Highways England) or
2. Regional Government (e.g. province of a country) or
3. Network operator as private investor besides their role as supplier of energy to an ERS system or
4. Joint venture (e.g. motorway operator, ERS supplier, third party).

Main factors limiting further deployment of ERS infrastructure

The main factors considered to limit the further deployment of ERS infrastructure can be considered to be as follows:

1. Taking the decision to implement an ERS system first on national level and to align / coordinate this among European countries
2. Inefficiency in terms of costs due to low level of usage and in terms of CO_2 reductions
3. Long distances from grid network to substation near the motorway, causing high costs on the grid operator side
4. Insufficient space for construction works on the motorway e.g. no break-down lane existing or no/limited access to site due to private property.

3.2 Road freight operators / trade associations

Journey lengths of HGVs

- Commodities of HGVs are extremely important when it comes to determining journey lengths – different commodities have very different duty cycles (e.g. concrete mixers) – construction vehicles, mining vehicles, delivery vehicles, and refrigerated trucks should all be considered separately.
  - **Ricardo comment**: following a review of available information, there does not appear to be a single source of journey lengths for different commodities of HGVs. Individual operators would have this data; however, this is beyond the scope of the current study.

- Stakeholders stated that the DfT should update their data collection to consider various commodities of HGVs.

Refuelling habits of HGVs

- Refuelling depends on operation – long-haul trucks will need to refuel on motorways, and this is dependent on when they take their breaks – this is dictated by the European Union rules on drivers' hours and working time.
- A lot of refuelling is carried out in home depots; drivers make use of fuelling cards outside of this refuelling behaviour. Local deliveries in smaller trucks will typically require vehicles to come back at night to refuel at the depot and would not require en-route refuelling. Long-haul trips would make more use of en-route refuelling.
- Refuelling also depends on the need of the business. Daily refuelling would be very rare; but every 2-3 days refuelling is common, dependent on the commodity.
- There will be a proportion of drivers for whom a vehicle will be idle at night; but it will be idle away from their depot. There are some vehicles that are manned all day every day, and as such they don't have time to refuel overnight (typically modern high-mileage articulated HGVs) – in this respect, support was given for a battery-assisted overhead catenary system on the motorway, as the vehicles are charging as they travel and have flexibility.
- It was noted that a system of overhead catenaries makes rational sense dealing with one kind of market (articulated) on a stretch of road that is heavily utilised.

Ultra rapid charging vs. depot charging for battery electric HGVs

- The importance of looking at the operation was noted, and where the depot is located.
- Freight operators are talking about having to change their method of operations and planning journeys made in electric HGVs, such as where they're going, how far their depot is from the destination, etc. Operators might look at depot charging more at the beginning, but as public infrastructure develops, they might then move away from depot charging because they can rely on en route charging.
    - **Ricardo comment**: this assumes that a network of ultra rapid charge points would be deployed, suitable for HGVs. Availability of this infrastructure would reduce the need for deploying depot-based charging infrastructure.
- With respect to charger power, it was noted that the freight industry will always prefer faster chargers (given a certain cost point), particularly as some vehicles are constantly in use.

Storage limitations for zero emission powertrain HGVs

- As vehicles get heavier, derogations (i.e. an exemption from or a relaxation of a rule or law) will likely be implemented to account for battery weight but this will develop as the market subsequently develops.
- The weight of an alternative powertrain must not negatively impact payload – if operators are sacrificing payload due to an increased weight of the battery / fuel cell, this will increase the number of vehicles on the road and increase congestion which in turn will increase emissions.
    - **Ricardo comment**: this assumes the HGVs already produce emissions, rather than having a zero-emission powertrain, although increased congestion can be costly.

Additional considerations / recommendations from road freight operators / trade associations

- For a fully zero emission fleet by 2050, all new vehicles will have to be zero emission by 2035; as such. All decisions will have to be made within the next 6-10 years.
- Policies developed outside of the existing vehicle lifecycle replacement can disproportionately affect and disadvantage SMEs – the natural replacement cycles of the vehicles must be considered and fully understood. Some lesser-used vehicles can last for 25 years.
- Whilst the government motivation on climate change is important, policies must consider the people and businesses doing the transition.

3.3 Road owners / operators

Operational considerations – battery electric HGVs

- The only barrier envisaged for highway operators is when an HGV runs out of charge. When battery electric HGVs are on the network, there is a question over how to recover them, particularly in an area where there is no hard shoulder. Recovery fleets may need to be enabled with recharging infrastructure, which may involve reequipping the recovery fleet.
- Mitigation against electric HGVs breaking down would be high frequency of charging stations on the network.
- The EU drivers' law currently states that drivers need to take a break every 4 hours. It was noted that this legislation should be considered for deployment of new technologies.

Operational considerations – hydrogen HGVs

- Similar to electric HGVs, there's no additional draw on physical infrastructure for highway operators; rather it's how they manage and assist vehicles powered by hydrogen, such as vehicle refuelling and breakdowns.
- Incident response is important to highway operators also – there is a query over whether an incident involving a hydrogen vehicle would have a greater impact than a fossil fuel vehicle.

Operational considerations – ERS HGVs

- Each gantry supporting the catenary system would be considered a structure under Highways England standards. There are strict regulatory requirements for these, and the lane would need to be closed to carry out physical inspections (the catenary systems are lightweight and wouldn't be able to support a walkway). The inspections would need to take place every two years, for every single gantry. Resourcing to carry out the inspections was highlighted as a very serious issue, to the point where it could be infeasible.
- One stakeholder noted an issue with respect to the heights of HGVs and over-height vehicles – whilst it's rare that HGVs have heights above a limit of just over 5m (e.g. abnormal load vehicles), larger vehicles do exist, which could potentially cause lane availability and congestion issues. A query was raised over whether ERS could increase the likelihood of incidence.
- If HGVs were confined to one lane with overhead infrastructure, it would make the lives of road owners and operators easier. Lanes would need to be closed for inspection or routine maintenance, so the HGVs would have to be equipped with an alternative power source.
- As a road operator, the first question is about the impact on traffic – under current policy, penalties occur between 6am and 10pm for lane closures, which are paid to the grantor (Highways England). Construction work would need to be carried out at night time, which is a big constraint from an operational perspective.
- A strong knowledge of the utilities in an area where ERS is being installed was deemed to be essential. Road operators have noted a lot of difficulties working with utilities to deploy

infrastructure, and a lot of administration work is involved. As such, testing ground for initial pilots should be very carefully selected.

Foreign HGVs with different zero emission technology coming into the UK

We asked numerous stakeholders on their views of foreign HGVs with differing zero emission powertrains coming into the UK than the zero-emission powertrain option chosen in the UK (i.e. incompatible infrastructure), and operational issues that could arise from this. Table 3.2 highlights the views of different stakeholders on this issue.

Table 3.2 Stakeholder views on foreign HGVs with different zero emission technology coming into the UK

No.	Stakeholder Views
1	• Other HGVs would be range-limited, particularly if the UK (or Europe) opts for ERS. Would be range-limiting for battery / hydrogen; and range prohibitive for ERS. • HGVs may need to swap trailers at an entry point to the UK (e.g. Dover). From an operator point of view, this would be advantageous, as tractor units would be UK-registered, which could assist with day-to-day housekeeping. However, a lot more infrastructure would be required at entry points, and every logistics operator would need a fleet on either side of the Channel. • Someone should take responsibility for ensuring the UK's solution is aligned with all if not the majority of Europe. Anything arriving by air / sea needs to be compatible. DfT was highlighted as being potentially suitable for this role – it needs to be applicable to both the strategic and local road network; and it's DfT that sanctions and funds infrastructure in the UK. • Tunnels and vehicle ferries may also prove to be problematic.
2	• This is not an issue – manufacturers will lobby for interoperability of the network. Irrespective of the technology that's chosen as being prominent in either the UK or Europe, manufacturers will ensure their vehicles are included. • Used the tolling industry as a comparative example.
3	• If every UK truck is required to be 100% zero emission, and non-zero emission foreign trucks are allowed into the UK, then the UK haulage industry is being put at a disadvantage. This needs to be done on a Europe-wide basis. International road haulage may not be able to be zero emission. • Need to consider how the markets behave – the differences in neighbouring countries need to be assessed and considered. • International cooperation is vital to ensuring interoperability – possibility of setting up a pan-European body.
4	• Flows are highly interconnected within Europe – it is totally crucial to set up a system in such a way that it is interoperable between European states (geographical Europe). Interoperability would be highly desirable despite Brexit. • Railroad is a negative example – there are different catenary systems, and different pantographs on the roofs of trains. European bodies should be responsible to set up coherent standards for interoperability – these tend to be driven by industry. Minimum standards should be set for the whole of Europe, and government should work with industry. • There should be a coordination role for Europe / the UK.

Road closures required to install ERS infrastructure

- At least two lanes would need to be closed for every installation. This would have to be undertaken as night work over multiple nights, unless contraflow is initiated, which would be for a major project (also involving speed reduction).
- Installation would involve a minimum of four visits per gantry, but this would not be over consecutive nights – the concrete would need to cure, as an example.
- Operationally, road operators tend to be limited to 4km of length of lane closure. If installing ERS, operators could install as much as feasible within that 4km. For contraflow projects (projects requiring re-routing of traffic via a temporary lane on the opposite carriageway, e.g. smart motorway), this can be carried out during the day, and the length limit increases to 10km.
- Gaps of 10km between lane closures must be maintained, but operators would not want to go 10km on, 10km off – this would make the scheme very unpopular very quickly. Logistically, operators would struggle to find a contractor with enough resource to do more than one 10km closure.
- Lane closures need to be booked a year in advance – road operators have their own schedule of road closures for routine maintenance, and efforts could be made to align the road closures. On a related note, it is important to phase the installations with renewals of pavements, and to align the two. Highways England is aware of their repairs schedule, and it could be phased with an existing lifecycle programme to optimise for cost and disturbance.

Cost of road closures

- An approximate cost for 4km of road closure = £2,000 per night. These costs would be higher for contraflow projects, but information on the costs for contraflow projects was unavailable. The £2,000 would be purely for traffic management rather than for the infrastructure.
- Road closure costs depend on what time it is. Penalty schemes are in place, and there may be large costs associated with installations depending on the time they are undertaken.
- Some sample road closure penalties are as follows:
    - 3 lanes closed on a Monday morning for one hour, with a 50mph speed limit: £18,314.
    - 2 lanes closed on a Monday morning for one hour, with a 50mph speed limit: £10,391.

3.4 Current ERS infrastructure operators

Cost and lifetime of ERS infrastructure

- The payback period depends heavily on the usage intensity. Therefore, it would be expected to decrease with ongoing market uptake of catenary trucks.
- The willingness to pay among the users depends on the overall cost difference between conventional and catenary trucks.
- It is quite impossible at the moment to calculate a meaningful payback period at least for the German case. It depends heavily on the intensity of use. Particularly in the early market phase, economic operation is not possible.

Operational challenges around deploying and operating ERS infrastructure

- One of the main challenges with deploying the infrastructure is to make sure during the planning process that there are good access points to the electrical grid.
- Safety issues should be considered, particularly with the pantograph. When you have a system in a large-scale market with pantographs and ownership of truck with pantograph, how do you make sure operators / drivers regularly check the pantograph?

- The system will primarily be on highways. The infrastructure for the German field trials was only installed on the outside lane – construction is on the outside of the road. A very short period is required to arrange everything over the outside lane. Some periods were needed to close the outside lanes in order to install the catenaries, but if it's on a highway with more than one lane then it will be less disruptive.

ERS infrastructure build rate limitations

- For the German demonstration projects, the time span was two years between starting and finalising the infrastructure; however, this should be considered as an upper limit. The planning procedure is very long in Germany – this can be considered a main barrier to deployment.
- With respect to the maximum number of kilometres that can realistically be constructed, Siemens (the infrastructure provider for the field trials) has stated that this should not be an issue – there is a not much a limitation on the infrastructure. Some years will be needed in the beginning to develop the team and assemble engineering knowledge, but once this has been achieved there will not be a big limitation on installations.

4 Key assumption criteria for modelling

This section provides a summary of all of the assumption criteria developed during this work and used in the modelling. The assumptions have been developed using a combination of Ricardo's previous work in this area, new research carried out as part of this work and input from stakeholder engagement.

4.1 Infrastructure assumptions

The key assumption criteria for the HRS capacity and costs are shown in Table 4.1. The equivalent assumptions for electric infrastructure are shown in Table 4.2 and for ERS in Table 4.3. The sources of the key assumption criteria are also detailed in this table.

Table 4.1 Key assumption criteria for HRS infrastructure (2018 prices)

Variable	Value			Source
	Low	Default	High	
H2 Capacity / day	400kg	800kg	1,200kg	Range of sources and previous Ricardo work.
CAPEX per station	£2,565,000	£3,420,000	£4,275,000	HTP project – managed by Ricardo. Previous Ricardo analysis of US market.
OPEX per station per year	4% CAPEX + Installation			Approximate based on HTP project – managed by Ricardo.
Installation cost per station	£100,000	£180,000		HTP project – managed by Ricardo. Previous Ricardo analysis of US market.
Network associated cost per station	£97,500			Based on network cost calculations from Ricardo previous work and compressor ratings in HTP project. Includes civil works.
CAPEX learning rate per doubling of installed capacity	0.90			Fuelling Europe's future (2013),
Installation learning rate per doubling of installed capacity	0.98			Ricardo estimate
Availability	75%			ETI Gas HGV infrastructure project

Table 4.2 shows the assumption criteria for charging infrastructure. These assumptions (CAPEX and installation cost) differ based on the charging power of the charger (detailed in row 2).

Table 4.2 Key assumption criteria for charging infrastructure (2018 prices)

Variable	Value			Source
	Low	Default	High	
Power	**7kW**	**22kW**	**>50kW**	**This is a header row.**
CAPEX per charger	£1,000	£2,000	£425/kW (assume ~50:50 CAPEX:Installation)	Fuelling Europe's future (2013), Ricardo analysis of US market
OPEX per charger	1.6%/1.2% (Depot/Public) OPEX + Installation			Ricardo analysis of US market
Installation cost per charger	£2500		Similar to CAPEX	Fuelling Europe's future (2013), Ricardo analysis of US market
Network costs/kW	£30		£350	Based on network cost calculations from Ricardo previous work. This includes civil and installation costs.
CAPEX learning rate per doubling of installed capacity	0.90			Fuelling Europe's future (2013),
Availability	65%			Ricardo analysis 22hrs a day for 252 operational days a year.
Depot chargers per vehicle	0.3 - 1			Ricardo analysis and literature review. Assumed there is provision for charging whenever a vehicle returns to depot. Variations are included for different vehicle class and sensitivities.

Table 4.3 Key assumption criteria for ERS infrastructure (2018 prices)

Variable	Value			Source
	Low	Med	High	
CAPEX/km	£875,000	£1,000,000	£1,250,000	Oeko Institute, 2018; Siemens
OPEX/km	£25,000	£50,000	£75,000	ECF - Trucking into a Greener Future: the economic impact of decarbonizing goods vehicles in Europe. Ricardo figures from US market.

Variable	Value			Source
	Low	Med	High	
Network costs/km	£350,000	£750,000	£1,250,000	Costs of the grid connection from Fraunhofer and Ricardo analysis. This includes civil and installation costs.
OPEX/km	4% of infrastructure cost/km			Oeko Institute, 2018
CAPEX learning rate per doubling of installed capacity	0.99			Ricardo estimate – Lower than others due to developed nature of technology from deployment for rail projects.
Availability	100%			Ricardo estimate

4.2 Vehicle assumptions

Information on the weights of different components within each of the vehicle size classes considered within the modelling was used to calculate the limits on available energy storage for each vehicle type – the breakdown of component weights is available in Appendix 2.

The assumptions relating to the vehicles are those which dictate the energy stored within the vehicle, i.e. battery capacity or hydrogen capacity for the various zero emission powertrain types. These assumptions are different for each vehicle class and have low, medium and high sensitives associated with them. They are presented in the following Table 4.4. These were generated from an assimilation of all of the information presented in this report, including the market review of vehicles (Table 2.5) and Ricardo analysis.

For the hybrid powertrains which use hydrogen (FCEV-ERS and FC-REEV), demand for hydrogen is calculated from the energy demand remaining once the electricity stored has been depleted. As such, a hydrogen storage capacity for each vehicle is not used. This was chosen as the calculation method as there are very few currently available or announced hybrid HGV powertrains that use hydrogen, on which to base the assessment. It is therefore assumed that a hydrogen tank sufficient in size to cover demand will be installed in the vehicles.

Table 4.4 Energy storage assumptions for different sizes of HGVs and different powertrain technology types

Powertrain	Fuel	Unit	Low	Mid	High
Small rigid HGV assumptions					
D-ICE	Diesel	litres	150	150	150
D-ERS	Electricity	kWh	5	5	5
D-REEV	Electricity	kWh	40	80	80
BEV	Electricity	kWh	150	200	500
BEV-ERS	Electricity	kWh	75	100	125
FCEV	Hydrogen	kgH2	15	25	35
FCEV-ERS	Electricity	kWh	5	5	5

Powertrain	Fuel	Unit	Low	Mid	High
FC-REEV	Electricity	kWh	40	80	80
Large rigid HGV assumptions					
D-ICE	Diesel	litres	500	500	500
D-ERS	Electricity	kWh	10	10	10
D-REEV	Electricity	kWh	70	140	240
BEV	Electricity	kWh	200	400	750
BEV-ERS	Electricity	kWh	150	200	250
FCEV	Hydrogen	kgH2	30	60	75
FCEV-ERS	Electricity	kWh	10	10	10
FC-REEV	Electricity	kWh	70	140	140
Articulated HGV assumptions					
D-ICE	Diesel	litres	500	750	1,000
D-ERS	Electricity	kWh	20	20	20
D-REEV	Electricity	kWh	100	200	400
BEV	Electricity	kWh	440	800	1,000
BEV-ERS	Electricity	kWh	200	300	400
FCEV	Hydrogen	kgH2	60	80	100
FCEV-ERS	Electricity	kWh	20	20	20
FC-REEV	Electricity	kWh	100	200	300

For scenarios involving battery electric HGVs, there is a requirement for chargers associated with each vehicle class, and these need to be differentiated between the vehicle sizes; for example, due to the higher power requirement for articulated HGVs, higher-powered ultra-rapid charge points need to be utilised. For this reason, there are different infrastructure assumptions for each vehicle class (small rigid, large rigid, articulated HGVs) – these are shown in Table 4.5. These are based on the market analysis in Section 2.3 and Ricardo analysis.

Table 4.5 Charging infrastructure power assumptions for different HGV size categories

Charger	Power (kW)		
	Low	Mid	High
Small rigid HGV charge point power assumptions			
Depot	7	22	50
Ultra-Rapid	150	350	500
Large rigid HGV charge point power assumptions			
Depot	22	50	100
Ultra-Rapid	500	700	1,000

Charger	Power (kW)		
	Low	Mid	High
Articulated HGV charge point power assumptions			
Depot	50	80	100
Ultra-Rapid	700	1,000	1,400

4.3 Finance Assumptions

Ricardo have used two finance models in this report – public and social. These have the assumptions shown in Table 4.6.

Table 4.6 Finance assumptions

Finance Model	Tax included (fuel duty, VAT)	Discount Rate
Social	No	3.5%
Private	Yes	7.5%

For financing calculations used in this work, the costs for CAPEX and installation are incurred from the year of installation until the finance period ends. Then, for annualised calculations, the OPEX is added as an in-year cost with no additional finance requirement.

5 Scenario development of market shares of HGVs

This section describes the market shares of different HGV powertrains that were developed for each of the scenarios to be utilised within the modelling of infrastructure costs and requirements. Each of the six scenarios are technology-focused and represent a push towards a certain powertrain technology, and each scenario considers three vehicle categories: small rigid, large rigid and articulated HGVs. The labelling of the six scenarios used in the analysis is as follows:

- Scenario 1 – Hydrogen
- Scenario 2 – Battery electric vehicle [Battery]
- Scenario 3 – Battery ERS [Bat-ERS]
- Scenario 4 – Hydrogen ERS [H2-ERS]
- Scenario 5 – Hydrogen range extender [H2-REX]
- Scenario 6 – Plug-in hybrid electric vehicle [PHEV]

As each of the scenarios represent a push towards a certain powertrain technology, some of the scenarios consider a mix of zero emission vehicle powertrain technologies within the market shares. As an example, within the Hydrogen scenario, it is assumed that a proportion of the small rigid vehicles will comprise battery electric HGVs, as small rigid vehicles operating in urban environments are considered to be well-suited to battery electric powertrains.

The CCC led on the development of the market shares of each powertrain technology type for each of the scenarios. The market shares for each scenario were developed using a combination of literature review, prior research and experience in the field of alternative transport fuels, stakeholder engagement and discussions during meetings. The trajectories for number of vehicles within the HGV fleet were developed using data supplied by CCC.

Each of the scenarios represent a rapid and ambitious uptake of zero emission powertrains for the HGV fleet. This study does not consider the rate of take-up of zero emission powertrains which depends on a number of factors including costs, government policy, and the manufacturing plans and capabilities of OEMs. Whilst this is an important aspect to note, the primary focus of this study is to estimate the costs and requirements of the infrastructure to support the transition to zero emission powertrain HGVs.

Figure 5.1 displays the market shares for new vehicle sales for the different powertrain technology types for each of the scenarios used within the modelling. The market shares presented within Figure 5.1 are for all vehicles combined (i.e. small rigid, large rigid and articulated HGVs). For each of the scenarios, it is assumed that the proportion of diesel sales will begin to fall after 2020 and stop by 2040 (although, there are some plug-in hybrid diesel HGV sales beyond this point, particularly in the PHEV scenario).

Appendix 3 presents the tables of new vehicle sales for each powertrain technology type within each scenario.

Figure 5.1 Market shares of different HGV powertrains for each scenario – new vehicle sales

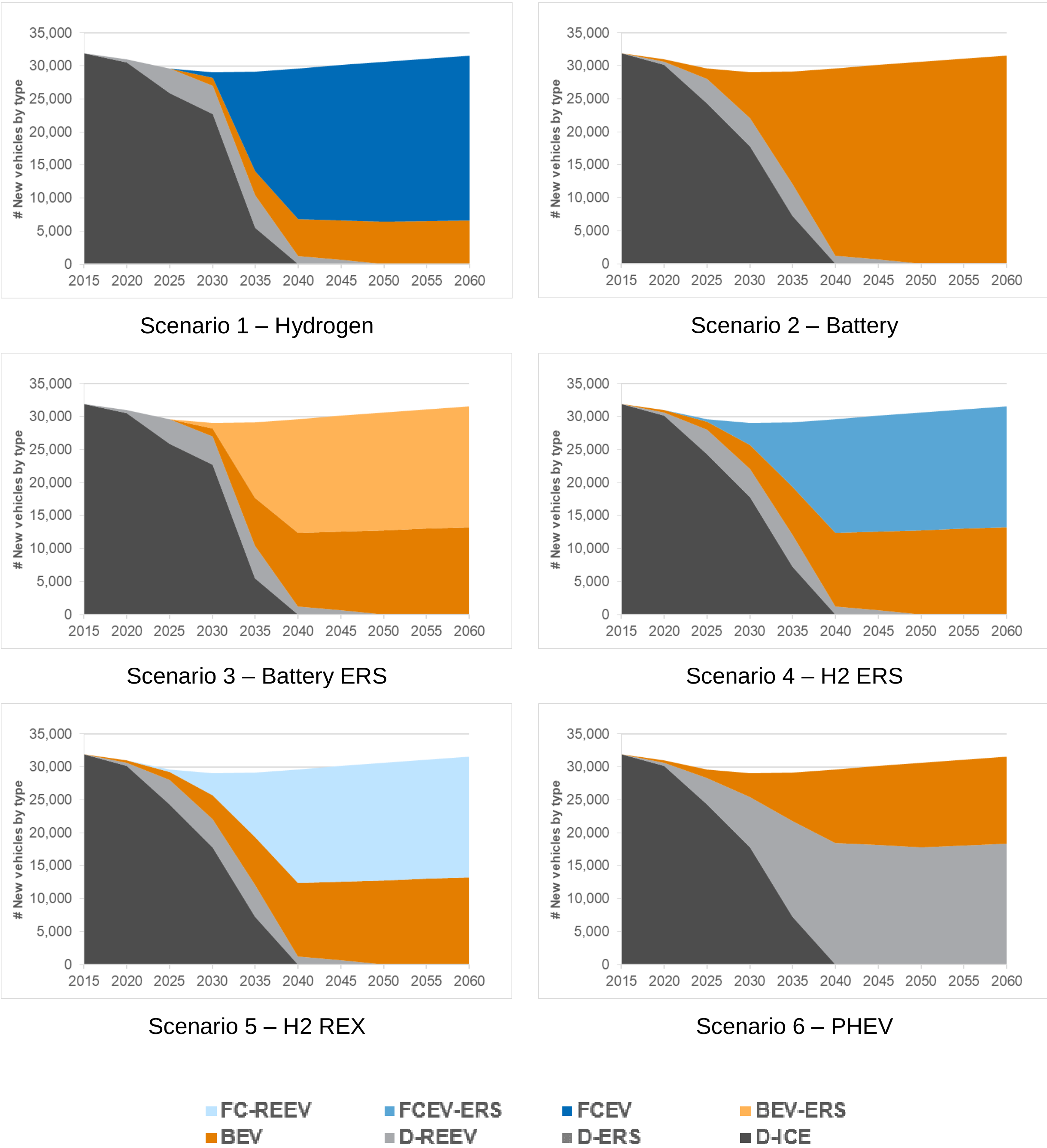
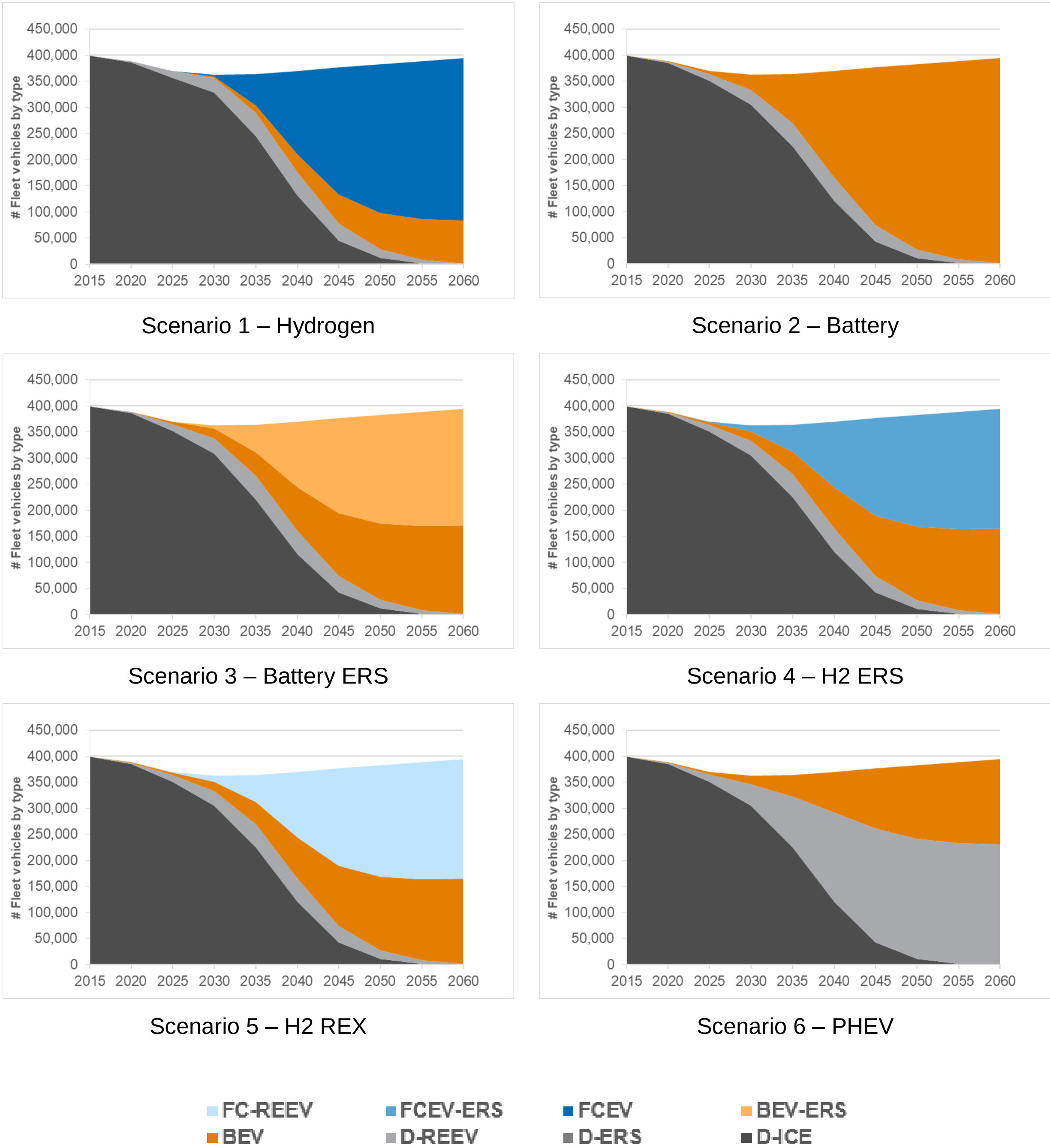


Figure 5.2 displays the market shares of different HGV powertrains for each of the scenarios based on the total number of vehicles considered within the analysis. It shows there is still a proportion of diesel-powered HGVs within the total vehicle fleet beyond 2050, due to the rate of replacement of some of the HGV fleet. Appendix 3 presents the tables of total number of vehicles in the parc for each powertrain technology within each of the scenarios.

Figure 5.2 Number of different HGV powertrains for each scenario – total number of vehicles in parc



6 Modelling infrastructure costs and requirements

This section provides a summary description of the methodology used to calculate zero emission (ZE) HGV infrastructure requirements.

We used two distinct approaches to estimate infrastructure needs:

1. **For point-based infrastructure** (i.e. charging stations, hydrogen refuelling stations), the requirements are based on a typical / average infrastructure unit capacity and the overall total amount of energy that has to be delivered by point infrastructure (i.e. less energy provided by depot-based charging / refuelling);
2. **For continuous / network infrastructure – i.e. ERS** – the length of motorway (and potentially also multiple-carriageway A-roads, depending on battery range / depot charging) needed to have ERS infrastructure installed to cover the required total vehicle-km on these roads.

Figure 6.1 presents a high-level schematic of the point-infrastructure calculations for charging and refuelling points, with colour coding used to show the differing stages of the modelling. Figure 6.2 displays a high-level schematic of the network infrastructure calculation, specifically for the ERS calculations.

Figure 6.1 High level schematic of the charging and refuelling (point) infrastructure calculations

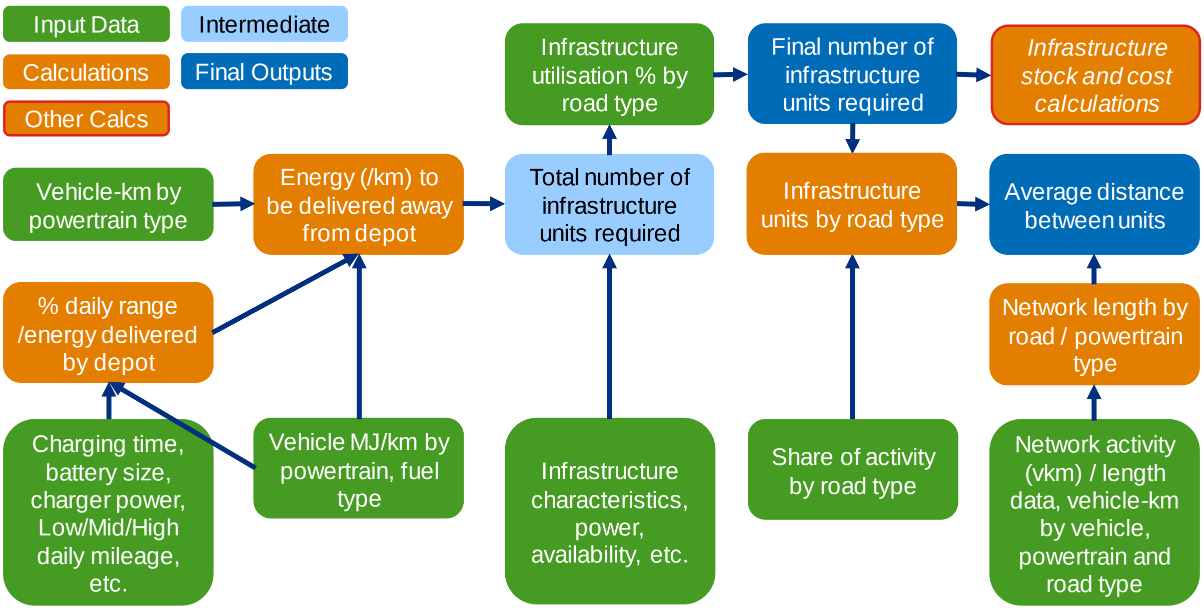
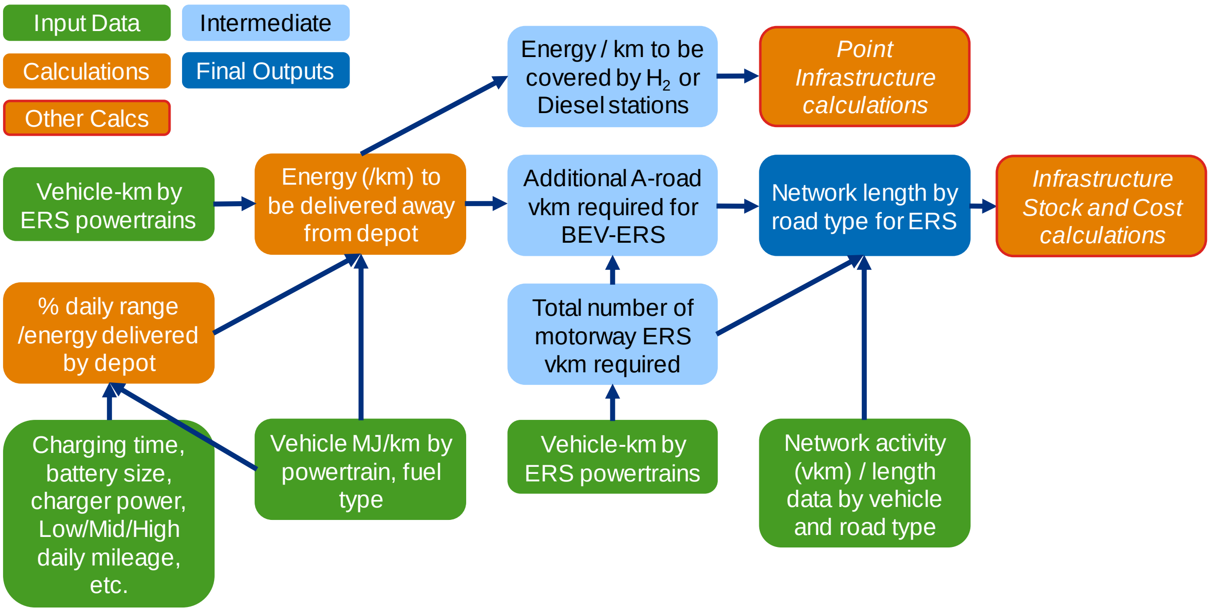


Figure 6.2 High level schematic of the ERS infrastructure calculations



6.1 Energy requirements

The initial estimation of infrastructure requirements is based on the amount of energy required to support the HGV fleet (i.e. depending on the different powertrain requirements). As discussed in Section 5, in all scenarios modelled the fleet is expected to comprise vehicles with a range of powertrains and fuel types. There is therefore a need for the model to calculate the energy requirements for hydrogen and electricity each time it is run, for the selected scenario.

Broadly, the system's energy requirement is defined as the number of vehicles multiplied by energy efficiencies and average journey distance (i.e. energy required equals energy efficiency (in MJ/km) x total annual vehicle km by powertrain type). Additional considerations are applied for individual powertrains. For those with batteries, the battery's reserved state-of-charge is also included (e.g. typically only 80-85% of a battery will be available to be used, with buffers provided to minimise deep discharge / overcharging that harm battery cycle life). For hybrid powertrains, the proportion operation on each fuel type/mode is also calculated, based on the variation in average daily mileage and the electric range (/electricity that can be delivered at the depot). The assumptions on the variation in daily mileage, which are summarised below in Table 6.1, were based upon data provided by CCC.

Table 6.1 Assumptions on the variation in daily mileage by HGVs

Mode	Daily km	% of Average Daily km	Working Day km	% Share of Working Days
Small rigid	Average	100%	96	40%
Small rigid	Low	46%	44	30%
Small rigid	High	156%	150	30%
Large rigid	Average	100%	265	40%
Large rigid	Low	46%	122	30%
Large rigid	High	156%	413	30%
Artic	Average	100%	507	40%
Artic	Low	52%	263	30%
Artic	High	156%	792	30%

Notes: Based on analysis of data supplied by CCC and assuming 250 working days per year.

6.2 Point-based infrastructure calculation

The minimum number of chargers/refuelling stations required to support the fleet's energy requirements is calculated based on predicted properties of refuelling and recharging infrastructure (as described in Section 4 above and based on the information gathering in preceding sections). Both depot and on-road infrastructure units are considered. Of note, the current form of the model assumes the only powertrains with significant reliance on depot infrastructure are BEV, BEV-ERS, Diesel (D-) REEV (/PHEV) and Fuel Cell (FC-) REEV.

It is assumed that all vehicles will undergo refuelling / recharging overnight or at the start of the day and that most powertrains, except pure BEV, will begin the day 100% charged / refuelled. It is not possible to guarantee BEVs will be fully charged overnight[5] due to constraints on charging time and likely E-Depot charger power. How much charge will be received from E-Depot chargers overnight is defined by the battery capacity, charger power and overnight charging time. The potential for multiple (mainly small rigid) HGVs to share depot chargers is accounted for, so that multiple vehicles (of different powertrain types) might achieve a full (or partial) charge, depending on the average numbers sharing a charger, the charger power and the total available time for charging.

For all powertrains, the maximum possible range from overnight charging / refuelling is then compared with the average range HGVs travel daily. Three range categories are included in this calculation (high, average and low) to model the variability of real-world driving practices as closely as possible (within feasible limits of complexity for the modelling). From this, the model calculates the average % of daily energy consumption covered by overnight and depot. Any remaining energy requirements must be supplied by road infrastructure.

There is also separate accounting for vehicles / vehicle-km that are not met by depot charging on average: (i) vehicle-km delivered by overseas vehicles not based in the UK; and (ii) a proportion of days where vehicles are away from their depot overnight (e.g. articulated vehicles with sleeper cabs doing 2-day trips).

6.3 Road Network calculation

The model also performs a parallel calculation to provide a sense-check that the implied numbers from the point-based calculation of infrastructure are realistic to provide reasonable coverage on relevant parts of the UK road network. This additional check is also provided by calculating an estimated 'average' distance between point infrastructure on motorways (based on the network length needed to deliver the relevant number of motorway vehicle km), and also on A-roads (though the latter is a less useful metric due to lower HGV activity on these roads).

The key inputs here are the total distance covered by HGVs, HGV network activity datasets and the network length corresponding to different levels of activity by HGVs on the different road types. This information is used to provide an indication of average spacing of the calculated numbers of recharging and refuelling units across the UK road network for major roads. If the average distance between infrastructure units is unrealistic (e.g. too large when compared to range of the vehicles, and/or equivalent spacing for diesel refuelling), the user can adjust the spacing via the 'utilisation' input table – this effectively increases the number of infrastructure units that are deployed (but by extension also reduces the amount of energy delivered by each unit).

6.4 ERS Road Network calculation

For the ERS infrastructure, the infrastructure is not point-based as with the other infrastructure types – it is dispersed in a continuous way over a range of roads (primarily motorways, but also A-roads if required for BEV-ERS vehicles). Therefore, the output from the model is the required length of ERS installation for the UK road network.

Analysis of information from the UK NAEI (managed by Ricardo for BEIS / Defra) was used to find the intensity of use, by HGVs, for all major roads in the UK[6]. This database includes information on the

[5] The model structure allows for this consideration to also be applied to other powertrains, thought this is not done in the current version.
[6] Based on analysis of detailed statistical traffic flow datasets by vehicle category from DfT derived from annual activity surveys using ANPR across the UK network.

traffic counts (i.e. number of vehicles passing a single point on a road per year) split out by vehicle type for all major roads in the UK. From this, the HGV usage intensity for various road types could be derived and ordered in terms of total cumulative annual vehicle km delivered by network segment (in km). A calculation could then be made of the length of ERS which is needed (from most intensively used road to least) which satisfies the vehicle constraints of range and journey distance.

The calculation is initially performed with respect to installation of ERS on the motorway network. For D-ERS and FCEV-ERS, it is assumed that all additional energy requirements / mileage away from the motorway-based ERS network are met through H2 or Diesel refuelling stations. However, for BEV-ERS powertrains, it is assumed any mileage that exceeds the range / energy provided by depot charging requires additional A-road ERS infrastructure.

6.5 Costs

The model also calculates a number of outputs relating to the costs of infrastructure of each scenario.

- Cost of building and maintaining the infrastructure (annualised and in-year).
- Net Present Values (NPV) for each technology, from both private and social perspective.
- Costs per vehicle, to the consumer and to society.

All of these are produced annually from 2020 to 2060[7].

[7] The initial project brief requested calculations up to 2050 or 'until it is feasible and cost-effective for 100% of the fleet to have transitioned to new technologies'. Based on initial modelling results, the time period was extended to 2060.

7 Results

This section presents the results of the modelling of the infrastructure costs and requirements for zero emission HGVs. The results are broken down as follows:

- Summary of results – provides the high-level comparison of the different technology-focused scenarios for cumulative costs;
- Scenarios – this section looks into each scenario individually and compares them to the other scenarios, in terms of costs and energy;
- Sensitivities – provides an overview of the methodology and results of the sensitivities run within the modelling.

7.1 Summary of results

This model focusses on the infrastructure costs of various market share scenarios for the HGV transport sector. From this analysis it has been found that the infrastructure to support a strong shift to the use of hydrogen as fuel for HGVs results in the lowest overall infrastructure costs.

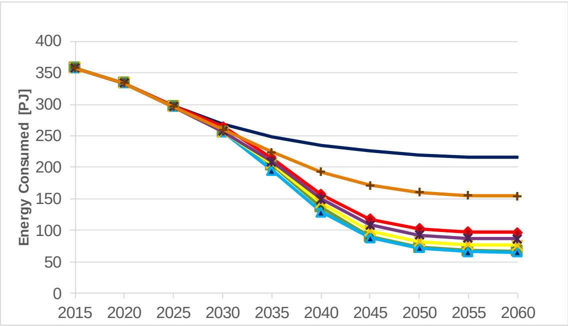
Table 7.1 below presents headlines figures on energy consumption and costs for the year 2060; Figure 7.1 contains the associated graphs, showing the results and trends in each scenario up until 2060.

Table 7.1 Cumulative CAPEX costs for infrastructure at 2060 for each scenario (2018 prices)

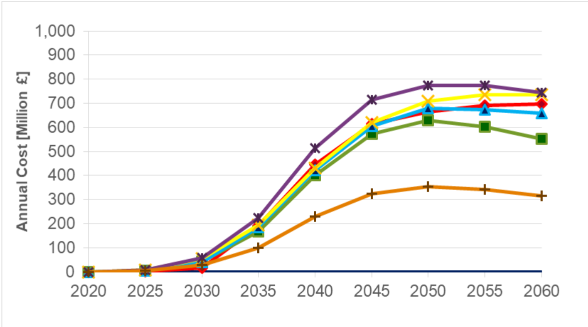
Scenario	Energy Consumed [PJ]	Annualised infrastructure cost at 2060 (societal – 3.5% discount rate) [Million £]	Annual fuel cost at 2060 (societal) [Million £]	Annualised fuel & infrastructure cost (societal) [Million £]	Cumulative CAPEX by 2060 (societal) [Bn £]			Cumulative total in-year costs by 2060 (including OPEX and fuel) (societal) [Bn £]		
					Low	Default	High	Low	Default	High
Baseline	216	£-	£2,954	£2,954	£-	£ -	£-	£148	£148	£148
Hydrogen	97	£698	£1,291	£1,990	£5.82	£ 7.7	£9.52	£129	£133	£137
Battery	67	£553	£858	£1,412	£10.74	£11.4	£12.07	£123	£123	£124
Bat-ERS	66	£660	£980	£1,640	£9.60	£10.4	£11.73	£126	£128	£130
H2-ERS	76	£735	£1,209	£1,943	£6.96	£ 8.5	£10.50	£129	£133	£138
H2-REX	86	£743	£1,074	£1,817	£9.73	£11.3	£12.83	£129	£132	£135
PHEV	155	£316	£2,021	£2,337	£6.14	£ 6.5	£6.85	£139	£140	£140

Notes: (**1**) Societal costs exclude all taxes. (**2**) The societal annualised cost calculations use a discount rate of 3.5%, and exclude all taxes. Annualised costs calculations convert capital expenditure into annual repayment costs over the relevant payback period (taken to be the infrastructure lifetime for a societal basis); where fuel and infrastructure operating costs are also included these are the average total costs of expenditure for a given year. (**3**) Total infrastructure costs include both the up-front capital expenditure (CAPEX) as well as operation and maintenance costs (OPEX). (**4**) In-year cost estimates do not include any annualisation of CAPEX costs, and simply represent all expenditure for the specified year. (**5**) Low / Default / High cumulative total in-year costs are sensitivities on the infrastructure costs only; there are no fuel cost sensitivities included.

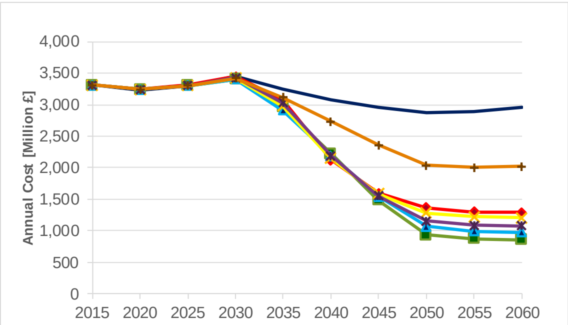
Figure 7.1 Cumulative energy and CAPEX results for infrastructure at 2060 for each scenario



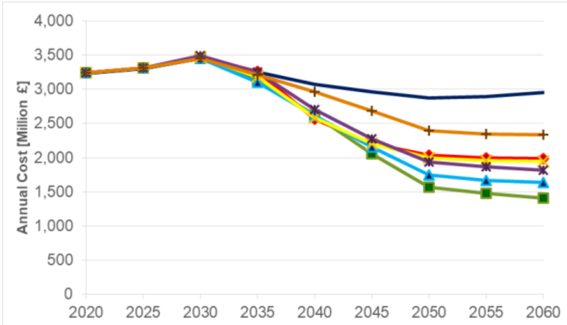
(a) Energy Consumed [PJ]



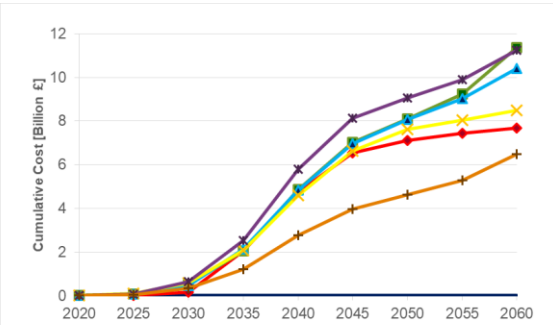
(b) Total annualised infrastructure cost p.a. (societal) [Million £] (1), (2), (3)



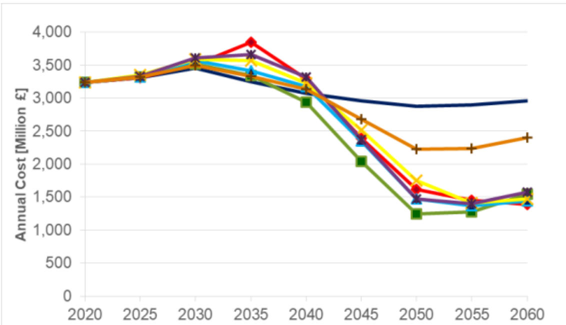
(c) Total annual fuel cost (societal) [Million £] (1)



(d) Total annualised fuel and infrastructure cost (societal) [Million £] (1), (2), (3)



(e) Cumulative CAPEX infrastructure costs (societal) [Billion £] (4)



(f) Total in-year fuel and infrastructure cost [Million £] (1), (4)

Notes: (1) Societal costs exclude all taxes. (**2**) The societal annualised cost calculations use a discount rate of 3.5%, and exclude all taxes. Annualised costs calculations convert capital expenditure into annual repayment costs over the relevant payback period (taken to be the infrastructure lifetime for a societal basis); where fuel and infrastructure operating costs are also included these are the average total costs of expenditure for a given year. (**3**) Total infrastructure costs include both the up-front capital expenditure (CAPEX) as well as operation and maintenance costs (OPEX). (**4**) In-year cost estimates do not include any annualisation of CAPEX costs, and simply represent all expenditure for the specified year.

As Table 7.1 and Figure 7.1 demonstrate, by 2060, the baseline scenario would require significantly more energy than all other scenarios modelled. Both BEV and BEV-ERS vehicles are much more efficient and have the lowest energy consumption in the sample. Of the remaining zero-emissions scenarios, PHEV has the highest energy requirements.

As shown in Table 7.1 and Figure 7.1(b), the infrastructure needed to support the transition to the three scenarios that include hydrogen (Hydrogen, H2-ERS and H2-REX) are the most expensive year-by-year. Whereas the annualised infrastructure costs for the Battery scenario is the lowest cost by 2060 (excluding the PHEV scenario which, although results in the lowest infrastructure cost, is not able to meet the zero emission target).

Considering the total annualised fuel cost, a different trend emerges: the fuel costs for the PHEV scenario are highest, whereas those relying on electicity (Battery and Battery-ERS) are the lowest. Comparing graphs (a) and (c) in Figure 7.1, it is clear that costs of a scenario are highly dependent on the energy consumed.

Figure 7.1(d) and Table 7.1 show the annualised costs of infrastructure and fuel combined. The baseline continues to be the most expensive option, due to its high fuel costs. Of the zero-emission scenarios, in 2060 Battery is the least expensive scenario, with £1.54 bn (52%) lower than baseline by 2060. This is followed by Bat-ERS, which is £1.31 bn (44%) cheaper than the baseline in the same year. PHEV is the most expensive of the modelled scenarios but is still £0.62 bn (21%) lower than the fossil fuel baseline by 2060, followed by the Hydrogen scenario (at £0.96 bn, 33% lower than the baseline).

Figure 8.1(e) and Table 7.1 shows the cumulative CAPEX figures at 2060 for all the scenarios, the costs for the PHEV scenario are lower than all the other scenarios. Of the other scenarios, Hydrogen and H2-ERS are the next cheapest, followed by Bat-ERS. Battery and H2-REX scenarios are then the most expensive. All infrastructure costs are relatively close together, when considering that they typically make the smallest contribution towards total costs, and are considerably lower than, for example, fuel costs.

It should be noted that the costs presented in Figure 7.1 and Table 7.1 do not include network upgrade or vehicle costs. As such, they do not represent the total economic cost of transitioning to these zero emission options. The inclusion of these additional costs could have a significant impact on which of the options present the lowest total economic cost. Appendix 4 contains the tabulated results for each individual scenario in five-year intervals, with tables available for vehicle energy consumption, annualised infrastructure costs, total annualised fuel costs, combined annualised fuel and infrastructure costs, and cumulative in-year CAPEX costs.

7.2 Scenarios

7.2.1 Energy demand for HGVs

For each scenario (excluding the baseline), the demand for energy decreases to 2050 and 2060, as shown in Table 7.2. This is due to the higher energy efficiency from all of the low emission technologies considered. The degree to which energy demand falls, therefore, is largely dependent on the energy efficiency of the powertrain.

Table 7.2 Energy demand comparison between 2015 and 2050, 2060 for each scenario

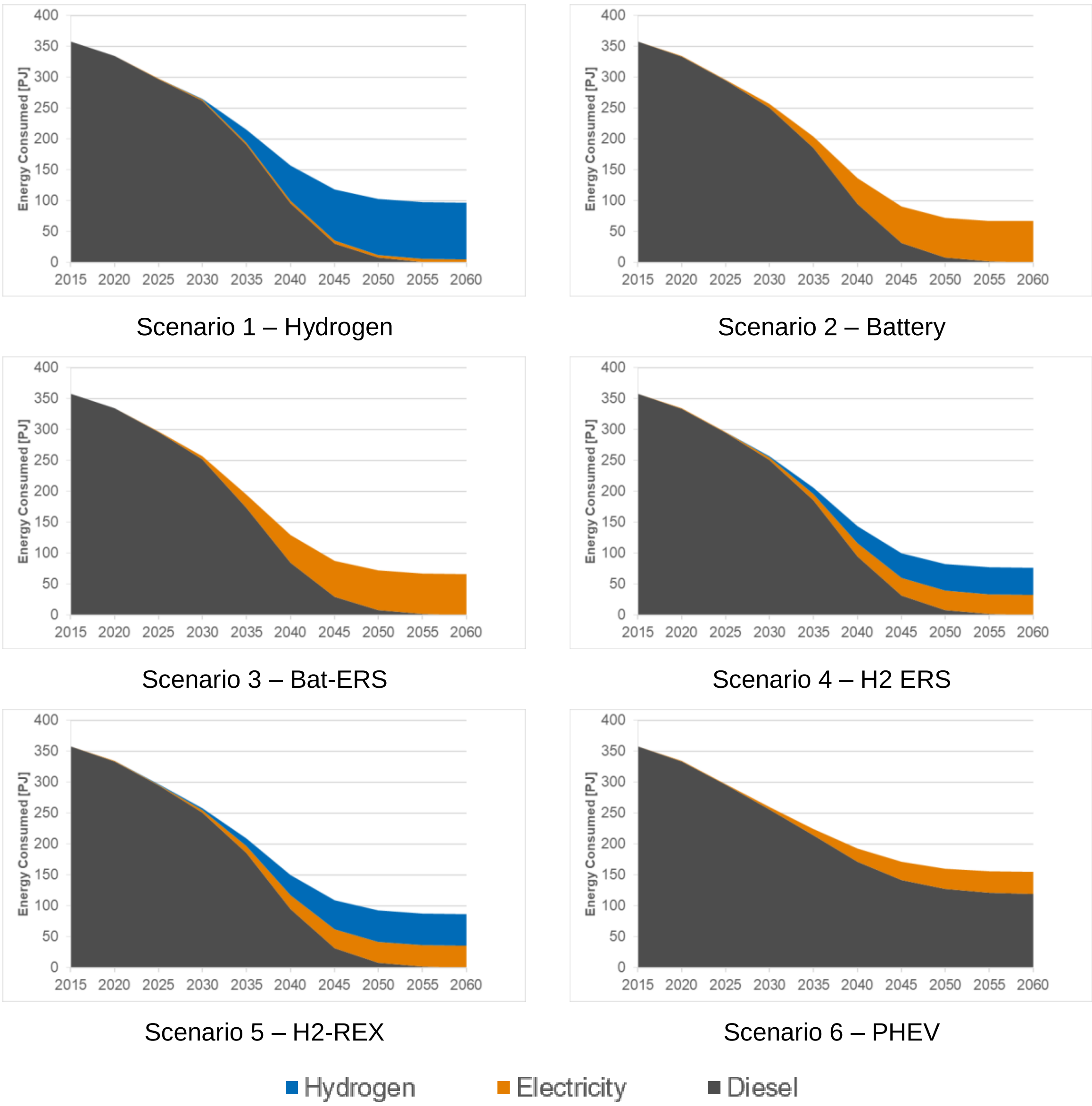
Scenario	Energy Consumed [PJ]			Percentage Reduction	
	2015	2050	2060	2015-2050	2015-2060
Baseline	357	219	216	39%	39%
Hydrogen	357	103	97	71%	73%
Battery	357	73	67	80%	81%
Bat-ERS	357	72	66	80%	82%
H2-ERS	357	82	76	77%	79%
H2-REX	357	92	86	74%	76%

Scenario	Energy Consumed [PJ]			Percentage Reduction	
	2015	2050	2060	2015-2050	2015-2060
PHEV	357	160	155	55%	57%

Figure 7.2 and Table 7.2 show the expected fall in energy demand for each scenario. The energy demand reduction is similar for the two electric scenarios (Scenario 2 – Rapid / Ultra Rapid chargers and Scenario 3 – ERS). This is lower (29% in 2050) than the energy demand from the Hydrogen scenario in 2050. The respective energy demand for hydrogen and electricity are similar for the H2-ERS and H2-REX scenarios (Scenarios 4 and 5) with roughly equal energy demand for both electricity and hydrogen. There is a 14% and 28% increase in total energy demand compared to the ERS scenario respectively. Due to lower vehicle efficiencies, the overall energy demand for the range extended hydrogen HGV scenario is slightly higher.

The PHEV scenario (Scenario 6) sees the lowest reduction in energy demand, although this is still substantial. 21% of the energy demand can be met with electricity, however there is still a continuing demand for 127 PJ of diesel by 2050. Appendix 4 presents the tabulated results on which Figure 7.2 is based, separated into five-year intervals for each scenario.

Figure 7.2 Vehicle energy consumption (by fuel), all Scenarios



7.2.2 Zero emission HGV refuelling infrastructure requirements

7.2.2.1 Number of units

The required infrastructure installations for each infrastructure type, within each scenario is shown in Table 7.3.

A significant requirement for infrastructure in all scenarios arises from the need for depot chargers. This is due to the low number of vehicles that can use a charger at any given time. Vehicles will tend to use depot chargers overnight or at other times when the vehicle is not in use, and our assumption is that between 0.3 and 0.85 depot chargers are needed per vehicle (when there is an electric element in the drivetrain). The requirement for depot chargers becomes very high in the Battery scenario with a requirement for more than 340,000 chargers in 2060. This is reduced in other scenarios, with ERS requiring approximately 260,000 depot chargers and the hydrogen related scenarios even less.

Table 7.3 Number of infrastructure units by type

	2020	2030	2040	2050	2060
Scenario 1 - Hydrogen					
E-Depot	708	16,091	51,346	67,713	70,310
E-Ultra Rapid	-	-	-	-	-
ERS	-	-	-	-	-
H2-Station	-	39	2,431	3,831	4,100
D-Fuel	4,293	3,368	1,225	95	1
Total	**5,001**	**19,498**	**55,002**	**71,639**	**74,411**
Scenario 2 – Battery					
E-Depot	1,686	39,643	200,183	315,836	340,893
E-Ultra Rapid	-	21	527	862	908
ERS	-	-	-	-	-
H2-Station	-	-	-	-	-
D-Fuel	4,290	3,225	1,220	96	1
Total	**5,976**	**42,889**	**201,930**	**316,794**	**341,802**
Scenario 3 - Battery ERS					
E-Depot	708	33,723	156,451	236,887	256,676
E-Ultra Rapid	-	-	-	-	1
ERS	-	114	1,956	3,572	3,849
H2-Station	-	-	-	-	-
D-Fuel	4,293	3,232	1,089	97	1
Total	**5,001**	**37,069**	**159,496**	**240,556**	**260,527**
Scenario 4 - H2 ERS					
E-Depot	1,686	29,097	89,259	128,237	139,815
E-Ultra Rapid	-	-	-	-	-
ERS	-	237	1,837	3,507	3,761
H2-Station	-	90	1,273	2,042	2,171
D-Fuel	4,290	3,225	1,220	96	1
Total	**5,976**	**32,649**	**93,589**	**133,882**	**145,748**

	2020	2030	2040	2050	2060
Scenario 5 - Range extended H2					
E-Depot	1,686	35,236	152,626	235,352	254,685
E-Ultra Rapid	-	-	-	-	-
ERS	-	-	-	-	-
H2-Station	-	112	1,550	2,414	2,563
D-Fuel	4,290	3,225	1,220	96	1
Total	**5,976**	**38,573**	**155,396**	**237,862**	**257,249**
Scenario 6- PHEV					
E-Depot	1,686	35,236	152,626	235,352	254,685
E-Ultra Rapid	-	-	-	-	-
ERS	-	-	-	-	-
H2-Station	-	-	-	-	-
D-Fuel	4,290	3,292	2,194	1,629	1,670
Total	**5,976**	**38,528**	**154,820**	**236,981**	**256,355**

All scenarios require E-depot chargers – this is due to the expectation of a fleet of small rigid electric trucks which would be present in any scenario (due to the already developed nature of this powertrain type). However, in all scenarios, the number of ultra-rapid chargers is relatively low. In all scenarios other than the Battery scenario, there is no requirement for ultra-rapid chargers, due to the availability of other sources of fuel.

In the ERS scenarios there is a large reduction in the requirement for other infrastructure. ERS in the Bat-ERS removes the need for nearly all[8] ultra-rapid chargers when compared to the Battery scenario. In the H2-ERS scenario, it removes the need for around 1,900 HRS, compared to the Hydrogen scenario. This means 2,171 HRS are needed when ERS is used in conjunction with HRS and hybrid H2-ERS vehicles. Between ERS battery and H2 ERS scenarios, there is a trade-off between the deployment of depot chargers and HRS with one effectively replacing the other in their respective scenarios. However, there is very little difference in ERS distance requirement required when comparing the two scenarios.

The Hydrogen scenario requires around 39 HRS in 2030, increasing quickly to 4,000 HRS by 2060. The HRS requirement for 2030 is significantly lower than other analysis done for the UK market, such as 1,000 HRS by 2030 (LowCVP, 2015) and a hydrogen road map which recommends 1,150 HRS are built in the UK by 2030 (UK H2Mobility, 2013). However, the scenario does show very rapid increase post 2030 which, could be more aligned with those other recommendations. The difference is likely to be due to differences in assumptions on penetration of hydrogen vehicles into the UK fleet, and analysis in this report only focusing on HGVs, compared with all vehicles being considered in other studies.

7.2.2.2 Build rates

In order to assess the feasibility of the shift to each scenario, it is important to look at the infrastructure build rates, which may be limited by real world deployment rates. No build rate limitations have been applied in this model – the build rate results are idealised, based on the expected demand increase for each infrastructure type in each given period.

The highest required unit build rate presented here is for the Electric Depot chargers. For each scenario this is between 5,000 and 20,000 units/year. As depot chargers are needed on a per-vehicle basis,

[8] The requirement for one ultra rapid charger is an artefact of the model assumptions. This results from there a requirement additional energy that could not be supplied either depot or ERS that warranted a single supercharger. The calculations do not link this one charger to any location or use case in particular.

rather than for a given energy demand, their roll-out is inherently inefficient and high numbers are needed. The total number of public charge points currently installed in the UK is 12,000, the majority of these have been installed since 2012, i.e. in the last 7 years. Whilst the power requirement for HGV chargers will be higher, the industry will be more advanced and as such, on the face of it, the roll out of depot chargers is likely to present a similar challenge to the industry. However, these HGV chargers will be needed over and above the much more rapidly growing demand for chargers for the light duty fleet and as such this could prove difficult.

For the ERS scenario, the peak build rate estimated is 274 km/year. Due to the early nature of this technology commercialisation, bottlenecks or industrial capability limits over their installation are not clear. However, from the literature, ERS infrastructure lengths in the order of thousands of km were predicted by 2050 for Europe, in light of this a build rate of 274km/year should not provide a significant barrier. This is in line with estimates from recent German studies examining maximum expansion level of ERS (such as (BDI, 2018), (Fraunhofer IML, 2017) (IFEU, 2015)). Build rates from such sources range from 135-350km/year.

An HRS peak build rate of 301 units/year is required in the Hydrogen scenario. This drops to 187 units/year for range extended H2 and 156 for H2-ERS. These numbers assume that small rigid HGVs mostly rely on EV charging. The Range extended hydrogen and H2-ERS build rates, and Hydrogen scenario's requirements in 2030 (8 HRS/year) and 2035 (171 HRS/year) appear achievable in the context of existing governmental announcements for H2 infrastructure; Germany aims to install 400 HRs by 2023 and a joint Scandinavian partnership aims to establish 150 by 2022 (Hydrgen Council, 2017).

However, the most ambitious roll out strategies today have not yet reached rates close to the peak build rates of the Hydrogen scenario. Infrastructure developments taking place in Germany installed 17 HRS in 2018 and another in California installed 41 to date (2012 – mid 2019) (AFDC, 2019) with plans for over 1,000 in the state. These build rates are the result of state or nationwide policy directives encouraging their roll-out. Additionally, this is roughly twice the build rates suggested in other literature[9] (e.g. (LowCVP, 2015) and (UK H2Mobility, 2013)). This difference from the Hydrogen scenario is again likely to be due to different assumptions on rate of hydrogen vehicle penetration into the fleet and considering HGV adoption rates that would result in zero fleet-level emissions by 2060. It is also likely that different studies made different assumptions regarding the average refuelling station size. The calculations here are based on a system energy requirement and assume a standard size of station.

Unlike some of the other studies, this analysis considered a scenario that was focused on Hydrogen as the primary decarbonisation means. When considering mixed Hydrogen scenarios such as H2-ERS and range extended H2, the build out rates of around 150 HRS per year, are more in line with other literature.

Table 7.4 shows a peak in diesel refuelling infrastructure in 2045, for all scenarios, which results from assumptions on the age of this infrastructure. No data was available on the age of existing infrastructure stock and therefore model assumes units are new in 2015. This matches the approach applied to other infrastructure types. The apparent sudden build rate peak in D-Fuel refuelling stations replacement of existing units that have exceeded their average lifespan and that are still required. In reality, this would be more gradual replacement occurring over a number of years.

For many of these infrastructure types, there has not yet been a significant roll out in the UK. As such, the factors which determine whether the implied build rates can be met are not yet known. It is likely that the availability of capital, the availability and skill level of the workforce, the planning and or power restrictions and government subsidies and policies will all play a role in defining the achievability of the infrastructure roll out rates presented here. These all remain open questions and present risks and opportunities for further work.

Table 7.4 shows the build rate in units/year over the modelled period for each scenario.

[9] Note: UK H2Mobility did not consider HGVs.

Table 7.4 Average build rate over 5 years [units/year]

	2020	2025	2030	2035	2040	2045	2050	2055	2060
Scenario 1 – Hydrogen									
E-Depot	138	1,088	1,919	3,581	3,661	3,518	2,812	3,887	3,670
E-UltraRapid	-	-	-	-	-	-	-	-	-
ERS	-	-	-	-	-	-	-	-	-
H2-Station	-	-	8	171	301	211	64	36	24
D-Fuel	-	-	-	-	-	149	-	-	-
Total	**138**	**1,088**	**1,927**	**3,752**	**3,962**	**3,878**	**2,876**	**3,923**	**3,693**
Scenario 2 - Battery									
E-Depot	330	1,913	5,525	12,704	20,015	17,658	13,173	15,752	20,945
E-UltraRapid	-	-	4	29	69	52	19	36	72
ERS	-	-	-	-	-	-	-	-	-
H2-Station	-	-	-	-	-	-	-	-	-
D-Fuel	-	-	-	-	-	134	-	-	-
Total	**330**	**1,913**	**5,529**	**12,733**	**20,084**	**17,843**	**13,192**	**15,788**	**21,018**
Scenario 3 - Battery ERS									
E-Depot	138	1,851	4,616	10,760	14,126	12,560	10,176	13,161	15,036
E-UltraRapid	-	-	-	-	-	-	-	-	-
ERS	-	-	41	100	274	237	104	38	35
H2-Station	-	-	-	-	-	-	-	-	-
D-Fuel	-	-	-	-	-	167	-	-	-
Total	**138**	**1,851**	**4,657**	**10,860**	**14,400**	**12,963**	**10,280**	**13,199**	**15,071**
Scenario 4 - H2 ERS									
E-Depot	330	1,748	3,614	5,778	6,677	6,752	6,512	7,211	7,167
E-UltraRapid	-	-	-	-	-	-	-	-	-
ERS	-	14	20	96	190	210	140	40	61
H2-Station	-	1	17	74	156	117	35	18	26
D-Fuel	-	-	-	-	-	134	-	-	-
Total	**330**	**1,763**	**3,651**	**5,948**	**7,023**	**7,213**	**6,687**	**7,269**	**7,254**
Scenario 5 - Range extended H2									
E-Depot	330	1,844	4,726	9,748	14,260	12,963	10,348	12,113	15,007
E-UltraRapid	-	-	-	-	-	-	-	-	-
ERS	-	-	-	-	-	-	-	-	-
H2-Station	-	2	19	90	187	134	34	20	31
D-Fuel	-	-	-	-	-	134	-	-	-
Total	**330**	**1,846**	**4,745**	**9,838**	**14,447**	**13,231**	**10,382**	**12,134**	**15,038**

	2020	2025	2030	2035	2040	2045	2050	2055	2060
Scenario 6- PHEV									
E-Depot	330	1,844	4,726	9,748	14,260	12,963	10,348	12,113	15,007
E-UltraRapid	-	-	-	-	-	-	-	-	-
ERS	-	-	-	-	-	-	-	-	-
H2-Station	-	-	-	-	-	-	-	-	-
D-Fuel	-	-	-	-	-	592	-	1	5
Total	**330**	**1,844**	**4,726**	**9,748**	**14,260**	**13,555**	**10,348**	**12,114**	**15,012**

7.2.3 Zero emission HGV refuelling infrastructure costs

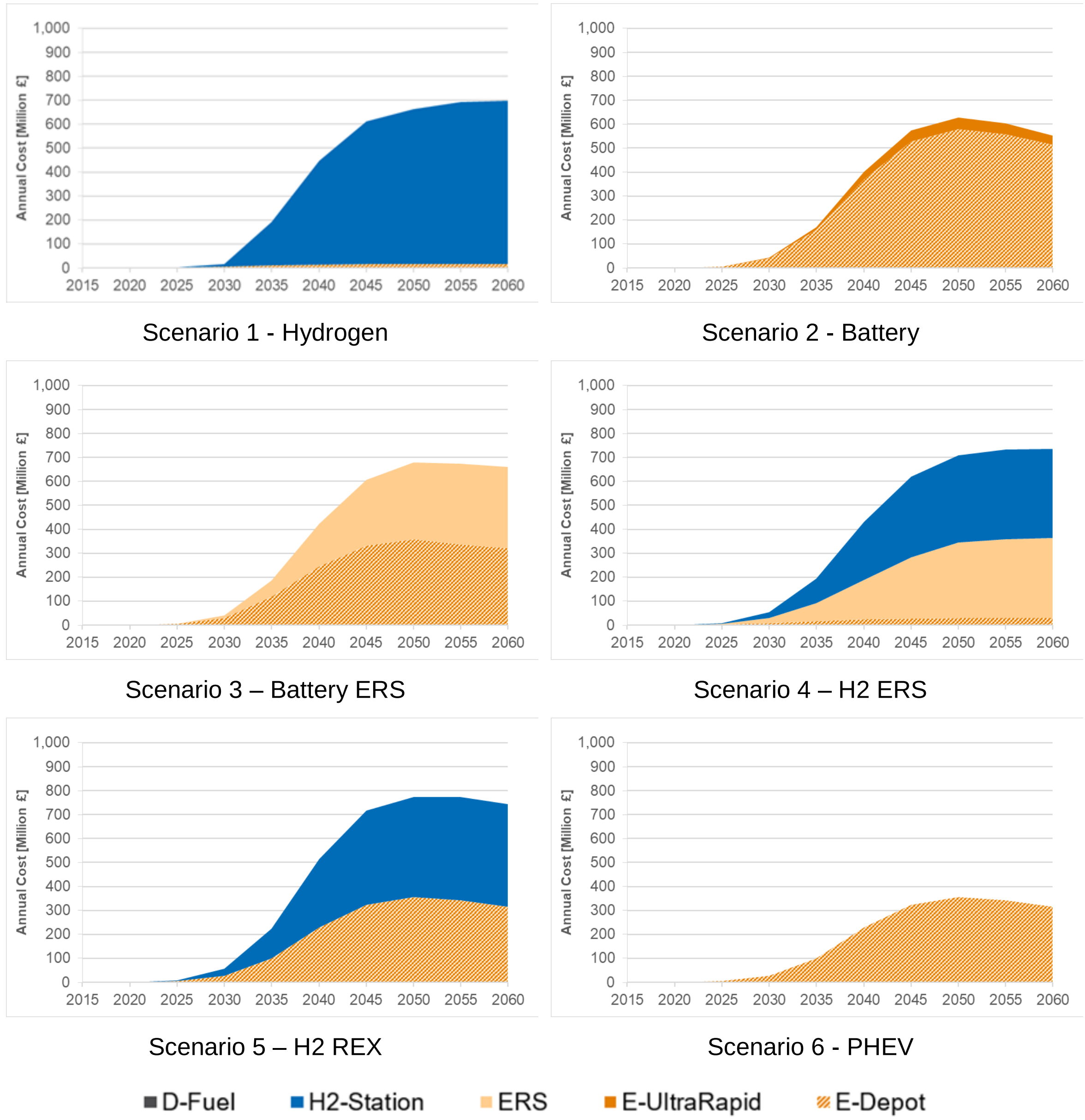
7.2.3.1 Annual infrastructure costs

The annual cost to society for the infrastructure is the sum of the total in-year costs arising from the infrastructure. This assumes that the financing of the purchase of the infrastructure (CAPEX) is at the social discount rate of 3.5%, the annual cost of this is added to the operation and maintenance costs (OPEX) costs for the infrastructure to calculate the overall costs. Figure 7.3 presents the results.

The total annual costs are highest for the range-extended Hydrogen scenario, costing £774m/year in 2050. This results from the high installation and CAPEX costs associated with HRS.

The two ERS scenarios are the next most expensive in 2050, with Hydrogen ERS costing £709m/year and Battery ERS costing £679m/year in 2050. These both require substantial refuelling infrastructure roll-out alongside ERS installation. In the Hydrogen ERS scenario, the majority of the cost (97.5% in 2050) are due to HRS. For the Battery ERS scenario, roughly half the cost is due to the depot chargers (52.8% in 2050) and half from the ERS installation (47.2% in 2050) (note that these figures are different to those quoted in the executive summary as those relate to cumulative CAPEX). For the remaining electric scenarios (Battery, H2 REX, PHEV), the annual cost of depot chargers dominates the overall infrastructure costs. Indeed, in the Battery scenario, a small proportion (~7%) of the infrastructure costs is not a result of depot chargers. Furthermore, annual costs are the lowest for PHEV (£355m/year in 2050) as it requires no ultra-rapid chargers (only depot chargers and mostly existing diesel refuelling stations). Tabulated data on which Figure 7.3 is based is presented in Appendix 4.

Figure 7.3 Total annual costs (societal), all scenarios [million £]



7.2.3.2 CAPEX Costs

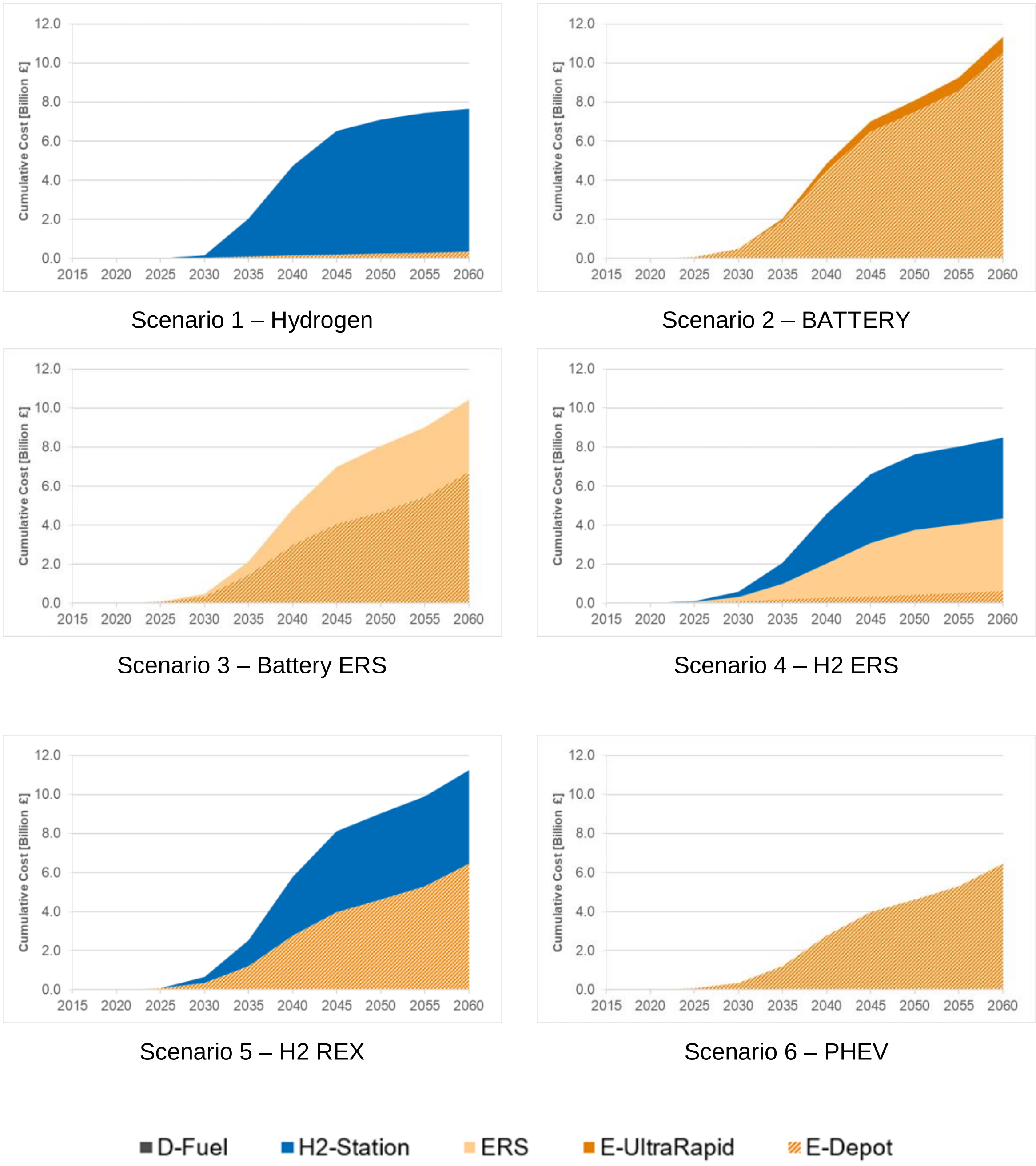
The CAPEX costs are largely similar to the costs shown above, however the cumulative figures show the total cost of infrastructure in each scenario to 2060. This is in the order of billions of pounds for all scenarios, as shown in Figure 7.4 (tabulated data for this figure is presented in Appendix 4).

Again, the CAPEX costs arising in the PHEV scenario are much lower than other scenarios. Costs arise solely from depot chargers, cumulative total of £6.5 bn by 2060. The costs of replacing and maintaining the existing diesel refuelling network have not been directly calculated in this project. Hydrogen is the next cheapest at £7.7 bn cumulative in 2060.

The Battery scenario is the most expensive, totalling £11.35 bn cumulative by 2060. Here infrastructure costs in the Battery scenario are dominated by depot chargers (93%). Indeed, a high proportion of the CAPEX costs for all the electric scenarios is due to depot chargers; 65% for ERS, 98% for Battery and 100% for PHEV (cumulative to 2060).

This is compared to Hydrogen scenarios, where HRS costs dominate: 4% of costs originate from depot chargers in the Hydrogen scenario and 7% for H2-ERS. Though depot chargers make up 57% of infrastructure costs for the H2-REX scenario, which contributes to it being the second most expensive scenario (£11.4 bn cumulative by 2060).

Figure 7.4 Cumulative in-year CAPEX costs (societal), all scenarios [billion £]



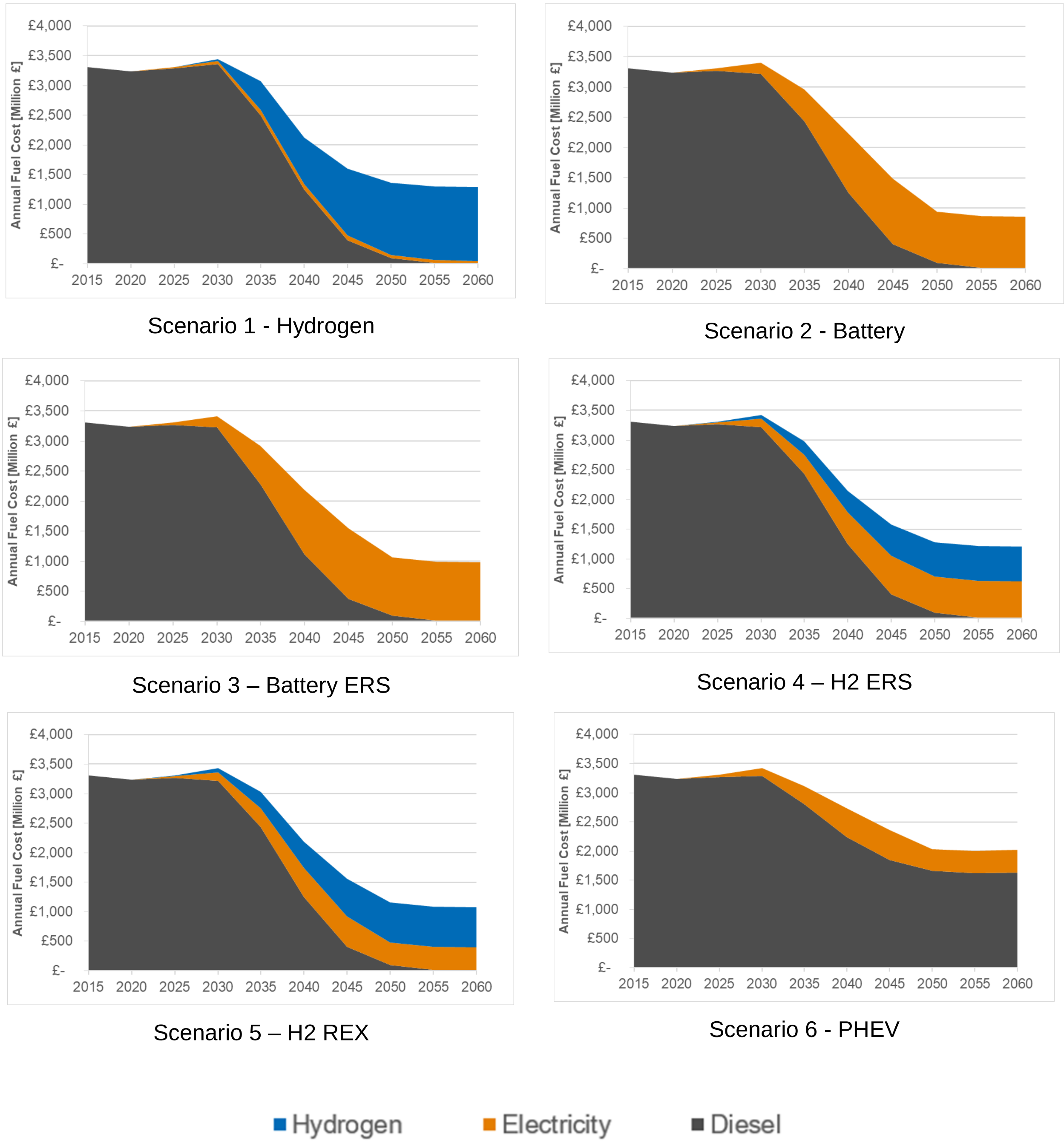
7.2.3.3 Annual fuel costs (social only)

Figure 7.5 shows the annual fuel costs excluding tax[10] for each scenario, split into diesel, electricity and hydrogen (tabulated data for this figure is available in Appendix 4). For all scenarios, the costs for fuel fall substantially when compared to the current fuel costs for diesel vehicles. This may lead to a capacity for investment in private recharging/refuelling infrastructure by fleet operators, providing a business case for the infrastructure investment needed.

[10] These are long-run variable costs for different fuels, excluding taxes.

Whilst the Hydrogen scenario leads to the lowest infrastructure cost, the fuel cost incurred by the HGV operators is the highest of any of the zero emission scenarios (£1.4bn per year in 2050) (the hydrogen fuel cost assumptions are based on production of hydrogen by electrolysis in the 2020s and a gradual switch over to hydrogen produced via SMR+CCS occurs in the 2030s). Fuel costs are lowest for the scenarios dominated by electric charging infrastructure (ERS and Battery) – they are roughly 30% lower than the Hydrogen scenario.

Figure 7.5 Annual fuel costs for each scenario (societal) [million £]



7.3 Sensitivities

In order to address how changes in various input variables affect the results, alternative model input cases are calculated. These input variations have been included in a number of sensitivities as shown in Table 7.5. These are designed to assess changes to the results arising from various scenarios; for example, the **Infra_LO** sensitivity looks at the case where the costs for all infrastructure types are lower than expected while all other parameters are kept at default level. For each sensitivity test case in the first column, a number of sensitivities can be included. Table 7.5 shows the input data which is adjusted for each sensitivity. For example, for the Infra_LO sensitivity, which describes the effect of lower than expected infrastructure costs, the low value of the cost of charging infrastructure, ERS and H2 station are used.

Table 7.5 Sensitivity definitions used within the modelling

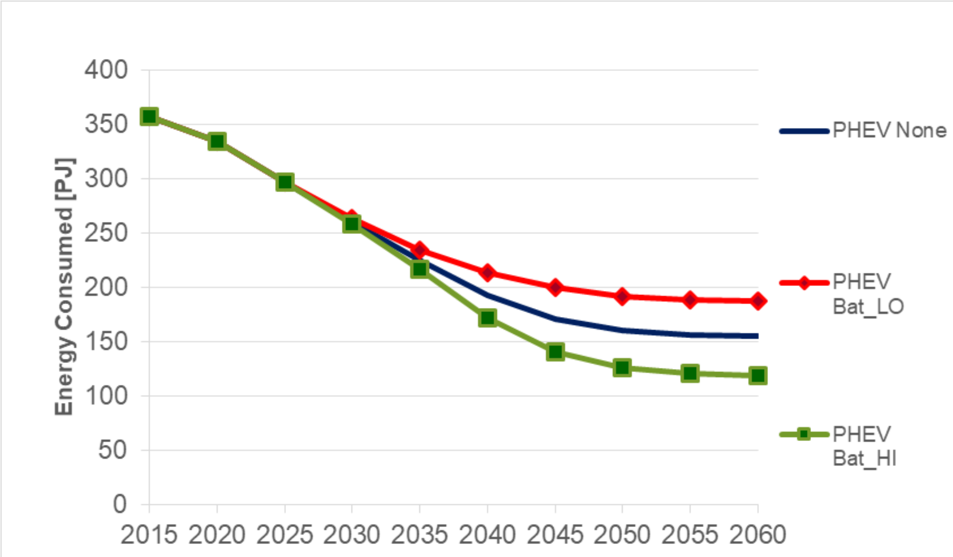
Sensitivity	Charger Cost	ERS Cost	H2 Station Cost	Network Upgrade	Battery Range	Battery Density	Depot Charger Cost
None	Default	Default	Default	Off	Default	Default	Default
Infra_LO	**Low**	**Low**	**Low**	Off	Default	Default	Default
Infra_HI	**High**	**High**	**High**	Off	Default	Default	Default
Bat_LO	Default	Default	Default	Off	**Low**	Default	Default
Bat_HI	Default	Default	Default	Off	**High**	Default	Default
NetUpg	Default	Default	Default	**On**	Default	Default	Default
BatAlt	Default	Default	Default	Off	Default	**Alt**	Default
Depot_LO	Default	Default	Default	Off	Default	Default	**Low**
Depot_HI	Default	Default	Default	Off	Default	Default	**High**

7.3.1 Energy demand for HGVs

Sensitivities have very little effect on the annual energy requirements. This is because energy demand is largely dependent on the fuel type, powertrain energy efficiency and total vehicle miles. None of these parameters were suitable for sensitivity analysis as they were based on data inputs provided by CCC, rather than assumptions within the model itself. The battery capacity sensitivities (Bat_HI and Bat_LO) have the greatest impact, yet these only affect the total energy consumed in 2060 by less than 1%. These results are therefore not discussed in any more detail.

Therefore, changes are seen in the PHEV scenario – Bat_HI -6.73% (-166 PJ), Bat_LO 6.93% (+160 PJ) difference compared to baseline scenario total energy consumption for PHEVs. When there is a high battery capacity, the PHEVs require less diesel. PHEVs operate (roughly 3 times) more efficiently in electric mode. These results are shown in Figure 7.6.

Figure 7.6 Energy consumed in scenario 6 (PHEV), low and high battery capacity sensitivities



7.3.2 Infrastructure costs

7.3.2.1 Infrastructure costs sensitivities

For all sensitivities, the H2-REX scenario remains the most expensive and PHEV the cheapest. The most significant variations from this sensitivity are for Hydrogen and ERS scenarios: Hydrogen, H2-ERS, H2-REX and Bat-ERS. In the high infrastructure sensitivity, in 2060, costs for these four scenarios are at least 25%, 24%, 17% and 16% higher than in the default sensitivity respectively. This is largely driven by H2 station and ERS costs which increase more significantly in the Infra_HI cost sensitivity than for other scenarios, as shown in Table 7.6 below, and Table 7.7 . These sensitivities are derived from literature review and Ricardo analysis.

Table 7.6 Cost sensitivities for hydrogen infrastructure [£]

Infrastructure	Default	Low	High
H2-Station, Capex	£3,420,000	£2,565,000	£4,275,000
H2-Station, Installation	£180,000	£135,000	£225,000

Table 7.7 Cost sensitivities for ERS infrastructure [£/km]

Infrastructure	Default	Low	High
ERS £/km	£ 2,000,000	£1,500,000	£ 2,500,000

Figure 7.7 presents the total annualised societal infrastructure costs by scenario for the low and high cost sensitivities. The results are tabulated for these sensitivities in Table 7.8.

Figure 7.7 Total annualised societal infrastructure cost by scenario, low and high infrastructure costs sensitivities, all scenarios

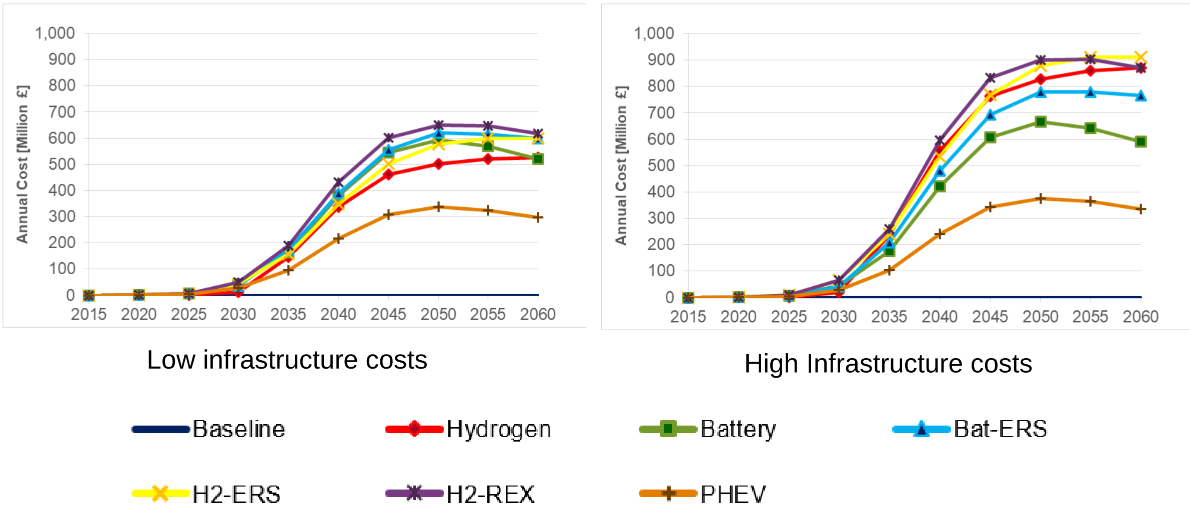


Table 7.8 Total annualised societal infrastructure cost by scenario, low and high infrastructure costs sensitivities, all scenarios [million £]

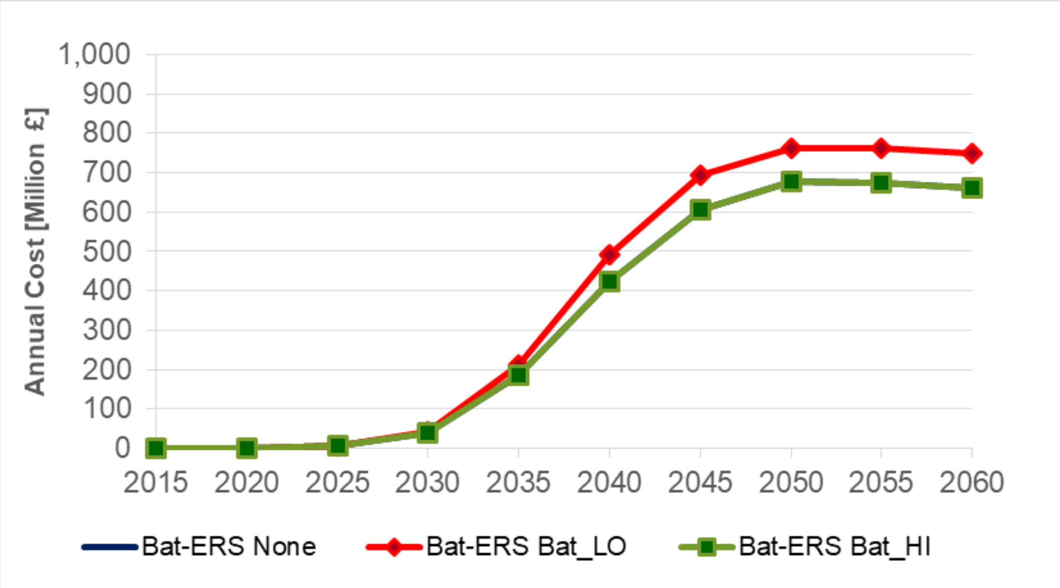
	2020	2030	2040	2050	2060
Low Infrastructure Costs					
Hydrogen	£0	£13	£338	£501	£527
Battery	£1	£41	£381	£594	£521
Bat-ERS	£0	£37	£389	£621	£600
H2-ERS	£1	£46	£349	£577	£599
H2-REX	£1	£50	£432	£651	£619
PHEV	£1	£27	£218	£337	£299
High Infrastructure Costs					
Hydrogen	£0	£19	£555	£827	£870
Battery	£1	£44	£423	£667	£591
Bat-ERS	£0	£43	£480	£780	£765
H2-ERS	£1	£67	£534	£880	£913
H2-REX	£1	£66	£597	£899	£870
PHEV	£1	£29	£240	£376	£336

7.3.2.2 Battery capacity

The cost of infrastructure is not sensitive to changes in the battery capacity for most scenarios. Throughout the scenarios, there is less than 1.5% change in costs compared to the default values. The exception is the Bat-ERS as shown in Figure 7.8 and the H2-REX scenario as shown in Figure 7.9.

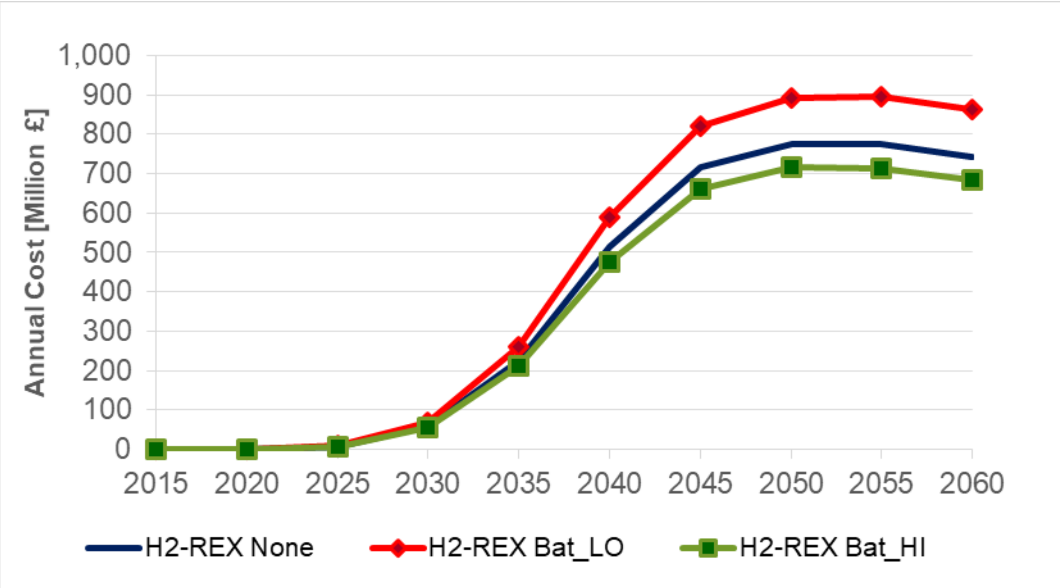
In the Bat-ERS scenario, the default sensitivity is roughly equal to the high capacity costs. However, there is an observable difference between the low and default (and high) battery capacity sensitivities. The reduction in battery range increases costs by 13% in 2060, due to an increase in the length of road that has to be fitted with ERS infrastructure in the modelling (an alternative could also be provision of Ultra-Rapid chargers to cover the additional off-ERS energy requirements, however this was not modelled). As the range of the battery increases, vehicles can cover a higher proportion of the journeys away from the ERS infrastructure, without charging.

Figure 7.8 Total annualised societal infrastructure cost by scenario, low and high battery capacity sensitivities, Scenario 4 (Bat-ERS)



For the H2-REX scenario (Figure 7.9), the high battery capacity sensitivity reduces costs by around 8% in 2060 and the smaller battery range scenario increases costs by 16%. In this scenario, there is still a need for electric depot chargers, however, in the Bat_LO sensitivity these do not provide as much energy due to smaller battery sizes. Therefore, there is an increase in overall costs of the infrastructure due to a higher demand for hydrogen and the higher associated costs.

Figure 7.9 Total annualised societal infrastructure cost by scenario, low and high battery capacity sensitivities, Scenario 6 (H2-REX)



7.3.2.3 Network upgrade

This sensitivity includes the calculation of costs associated with electric network upgrades. The costs assumed for the network upgrades necessary for each charger are shown in Table 7.9.

Table 7.9 Network upgrade costs for electric chargers

Infrastructure	Unit	Value
H2 Station	£/station	97,500
E-Depot (22kW)	£/kW	30.0
DC chargers (>50kW)	£/kW	350.0
ERS	£/km	750,000

As a result, there is a cost increase in all scenarios where the fleet contains a high proportion of electric powertrains HGVs:

- Scenario 1, (Hydrogen), 3.2% increase in 2060.
- Scenario 2, (Battery), 33% increase in 2060
- Scenario 3, (Bat-ERS), 36% increase in 2060
- Scenario 4, (H2-ERS), 36% increase in 2060
- Scenario 5, (H2-REX), 15% increase in 2060
- Scenario 6, (PHEV), 31% increase in 2060

Figure 7.10 presents the results of the analysis of network upgrade costs; whilst Table 7.10 tabulates the results in 10-year intervals.

Figure 7.10 Total annualised societal infrastructure cost by scenario, network upgrade, sensitivities, all scenarios

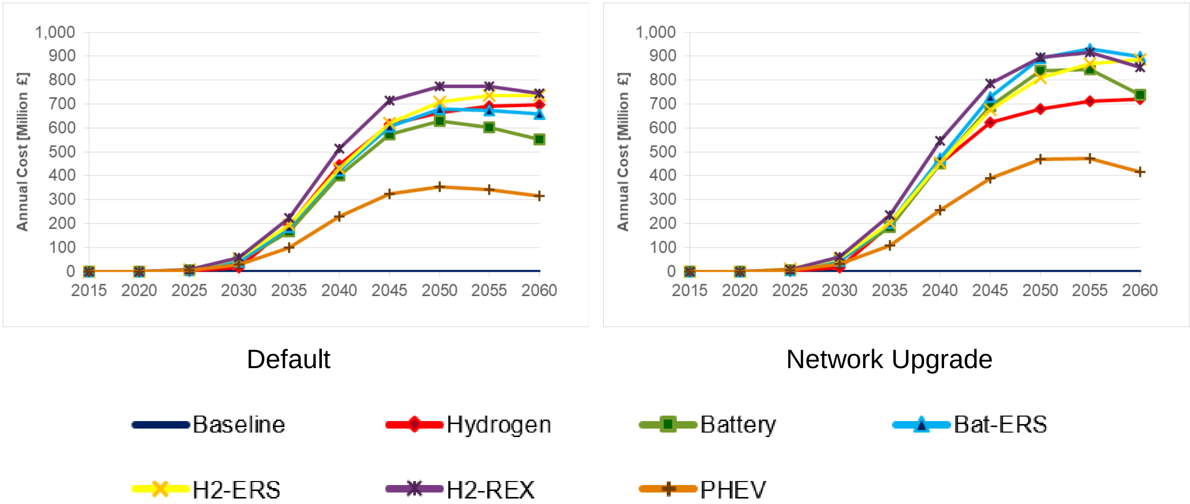


Table 7.10 Total annualised societal infrastructure cost by scenario, network upgrade sensitivities, all scenarios [million £]

	2020	2030	2040	2050	2060
Hydrogen	£0	£17	£450	£680	£721
Battery	£1	£46	£453	£839	£737
Bat-ERS	£0	£43	£474	£893	£898
H2-ERS	£1	£57	£456	£809	£886
H2-REX	£1	£60	£545	£896	£855
PHEV	£1	£30	£258	£468	£416

7.3.2.4 Battery energy density

The battery density sensitivity has minimal impact on the costs of infrastructure as there is very little resultant effect on the overall energy demand (as battery energy density does not affect the energy demand of the vehicle in the modelling method used and potential increases in density are not sufficiently high to negate the need for non-depot infrastructure). For all scenarios, this sensitivity results in less than a 0.1% change in costs. These results are therefore not discussed in any more detail.

7.3.2.5 Depot charging

In this sensitivity, the relative need for depot chargers amongst HGV fleets is examined. For the default calculations, there are between 0.5-0.85 depot chargers per vehicle. To test the sensitivity to these variables, alternative values are used, these are shown in Table 7.11. This is a critical sensitivity due to the uncertainty surrounding fleet operation characteristics under new powertrain types.

Table 7.11 E-Depot to charger ratio sensitivities

	Default	Low	High
D-ERS	0.000	0.000	0.000
D-REEV	0.500	0.330	0.750
BEV	0.850	0.800	1.000
BEV-ERS	0.500	0.330	0.800
FCEV-ERS	0.000	0.000	0.000
FC-REEV	0.500	0.330	0.750

The difference in annualised infrastructure costs for each scenario in 2050 is shown in Table 7.12, and the results for the low and high sensitivities are presented in Figure 7.11 and tabulated in Table 7.13. The infrastructure costs for all scenarios which have a reliance on depot chargers are highly sensitive to depot charger ratios. As a result, PHEV, H2-REX and Bat-ERS costs vary most significantly with the changes in E-Depot charger. The sensitivity for the Battery scenario covers a smaller range of values due to assumed operational constraints which are not present for other scenarios.

Table 7.12 Change in annualised infrastructure costs due to depot charger proportion sensitivities in 2050 compared to default sensitivity

Scenario	Depot Low	Depot High
Hydrogen	< -1%	< 1%
Battery	-5%	12%
Bat-ERS	-14%	24%
H2-ERS	0%	1%
H2-REX	-13%	18%
PHEV	-29%	43%

Figure 7.11: Total annualised societal infrastructure cost by scenario, Depot charging sensitivities, all scenarios

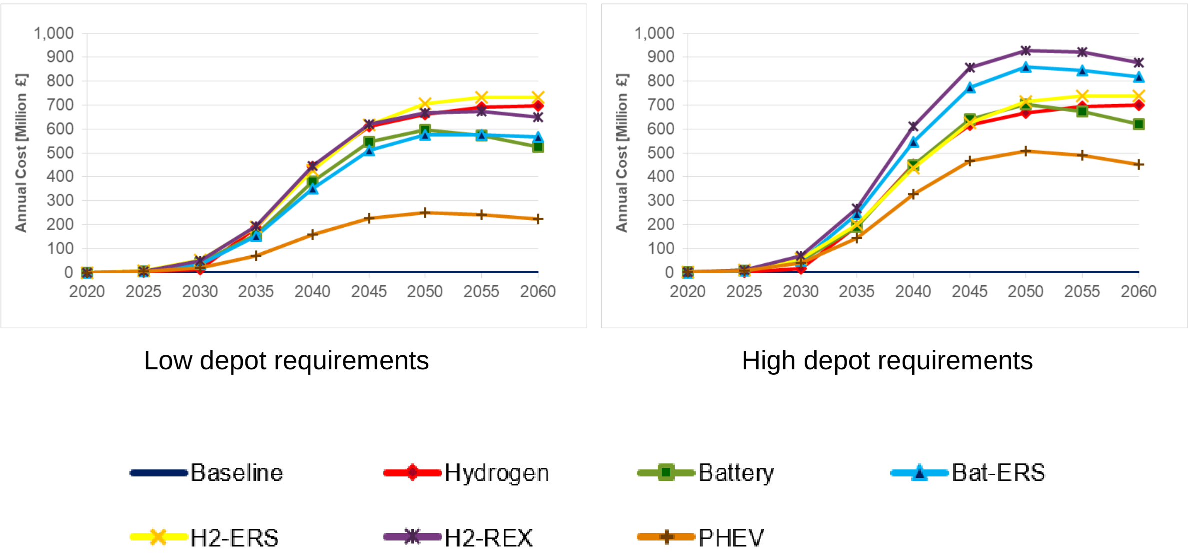


Table 7.13 Total annualised societal infrastructure cost by scenario, depot charging sensitivities, all ZE scenarios [million £]

	2020	2030	2040	2050	2060
Depot low					
Hydrogen	£0.2	£15	£444	£663	£698
Battery	£0.5	£40	£380	£597	£526
Bat-ERS	£0.2	£33	£352	£574	£568
H2-ERS	£0.5	£53	£428	£707	£733
H2-REX	£0.5	£50	£445	£668	£650
PHEV	£0.5	£20	£160	£250	£223
Depot High					
Hydrogen	£0.4	£18	£450	£667	£701
Battery	£0.7	£50	£449	£702	£619
Bat-ERS	£0.4	£51	£545	£860	£820
H2-ERS	£0.7	£57	£436	£714	£740
H2-REX	£0.7	£70	£613	£928	£879
PHEV	£0.7	£40	£327	£509	£452

8 Discussion on zero emission HGV infrastructure requirements and costs

The main aim of this project was to calculate and present the infrastructure costs which would be incurred through a concerted effort to decarbonise the HGV sector by 2050. It was found that, when only considering the infrastructure and fuel costs, a shift to BEV HGVs is the lowest cost option. This aligns with trends seen in the light duty vehicle sector, where a large shift towards BEV electrification is underway.

In the LGV sector BEV (and PHEV) models have become more widely available with costs falling rapidly and have the option for relatively low-cost home / depot-based charging. The charging requirements for electric HGVs are more challenging. The much higher energy requirement and hence larger batteries in HGVs compared to light duty vehicles, means that depot chargers (which are primarily used overnight) need to have much higher power output (in this project this is assumed to be 50-100kW for articulated HGVs). At this level of power, all chargers are DC, which significantly increases the cost and complexity of the charging points on a per kW basis. This is the main source of infrastructure cost for the deployment of BEV HGVs. Because of this, from a purely infrastructure perspective (cumulative CAPEX), battery and Bat-ERS scenarios are more expensive than Hydrogen, with the Hydrogen scenario being approximately 50% cheaper than Battery by 2060.

However, when considering cumulative infrastructure and fuel costs, the Hydrogen options result in the highest costs while the BEV and BEV-ERS options in the lowest costs. It is assumed that there remains an additional EV charging infrastructure requirement in the Hydrogen scenarios due to the assumption that most small HGVs will be electric. It is assumed, based on the research carried out in this project, that it is mostly the larger rigid and articulated HGVs that make the transition to hydrogen fuel cells. Therefore, despite hydrogen's higher energy density, a combination of significantly lower energy efficiency than BEV and lack of ability to utilise depot charging for larger HGVs, leads to much more energy needed to be delivered in the Hydrogen Scenario than in the Battery and Bat-ERS scenarios. Most of this energy is delivered via HRS, with no ability for larger vehicles to utilise depot-based charging. Thus, resulting in more HRS than ultra-rapid chargers being required. The combined fuel and infrastructure costs in the Hydrogen scenarios are around 8% higher than in the Battery scenario.

As already indicated, the focus of this report has been on infrastructure and fuel costs, rather than whole system costs of the different ultra-low carbon options for HGVs. Other factors are important and will have a large bearing on the overall system costs and purchase intentions of fleet managers and HGV operators. For instance, the vehicle purchase cost is not considered here, this may drop quickly for some scenarios (such as Battery or PHEV) due to synergies with the light duty vehicle sector where the large shifts are driving battery costs down quickly (although the higher up-front investment for depot chargers would counter-act this). Changes to current HGV operational practises could also have an impact on infrastructure costs. For example, if (due to the need for high power, DC chargers) depot charger costs are very high for fleet operators, and public infrastructure is relatively cheaper and easy for them to use (i.e. without the significant up-front investment), there could be a change to the assumptions made in this report due to changes made in vehicle operations.

One example would be a lower take-up in depot chargers amongst the HGV fleet and a greater usage of public charging infrastructure (should this be made available), resulting in a more efficiently used charging network and lower overall infrastructure costs than those presented here. Although, in order to maintain good battery state of health, regular "slower" charging cycles are needed to balance out battery cells, meaning some access to overnight / depot charging is likely unavoidable. Nevertheless, there is also likely to be a degree of optimisation to be reached between battery size / electric range and infrastructure investment – i.e. it may be feasible to reduce the size of the on-board batteries (within operational constraints) to save vehicle CAPEX cost, with a relatively more modest increase in public charging infrastructure requirements / cost (i.e. to cover energy no longer covered by the range of the batteries). However, a further consideration is that grid reinforcement costs have not been included in our analysis (these are being covered by a separate project). These additional costs are likely to be very high for ultra-rapid chargers, so increasing the number of those required would also increase these costs.

There are significant savings in fuel costs, relative to diesel, for all scenarios considered. This could offset some of the cost of investment in depot chargers or other private refuelling infrastructure by the fleet operators. The scope for offsetting infrastructure costs through fuel cost savings is largest in the

Battery and Bat-ERS scenarios as these have the largest reduction in fuel costs. PHEVs are the only electric powertrain to perform poorly here; it results in the highest fuel costs due to its maintained reliance on diesel. Although, these costs are still lower than baseline fuel costs. The three hydrogen options follow as the next most expensive.

Network / grid reinforcement costs have not been analysed in detail for this project (as they are subject to a separate analysis by CCC) and are therefore excluded from the basic infrastructure cost analysis presented here for all types of infrastructure. However, a simple high-level sensitivity on these has been presented to give an indication on their potential magnitude of these costs, based on previous high-level analysis by Ricardo in this area (see Section 7.3.2).

8.1 Risks and barriers

8.1.1 Infrastructure build rate limitations

Build rate limitations are not thought to pose a significant constraint for most infrastructure components. However, this is a complex area to consider that includes considerations for availability and skill-level of required labour, resource and material availability, planning permission processes, government policy and market landscape, and therefore, requires more in-depth investigation.

The estimated number of ultra-rapid chargers needed by 2050 in the Battery scenario is relatively low (around 862), based on the assumed battery sizes for such vehicles with a peak annual build rate of 72. Based on current industry experience and technology developments from the light duty vehicle sector, this is probably the easiest infrastructure requirement to meet.

The peak build rate for HRS needed within the Hydrogen scenario is 301 per annum, and the total about 4,100 This appears to be ambitious, when comparing the rapid roll out of this infrastructure taking place currently in California (total of 341 HRS now installed (2012 – mid 2019) with plans for over 1,000 in the state) and Germany (17 new HRS in 2018).

The ERS infrastructure is more disruptive and likely to be more difficult to meet. This is due to the need for road closures and increased planning time compared with other infrastructure types. However, stakeholders suggested that once operational capability has been proven for ERS, the speed of roll out could be very fast. Therefore, the build rate capability is thought to be above the 274km/year peak that was estimated as necessary in the ERS scenario. The availability of skilled workers could be a constraint for such widespread rapid deployment of ERS.

The demand for depot chargers is expected to rise dramatically in all scenarios (on the assumption that overnight depot charging is the least operationally disruptive option). It is unclear whether this increase in demand for depot chargers might provide a bottleneck due to the ability of the industry to meet demand for both the light-duty and heavy-duty sectors and provision of grid upgrades (although new technologies may ease the transition – such as smart charging technologies, energy storage and co-location with renewables, such as the solution being deployed at a UPS depot in London). The light duty electric vehicle market is currently expanding rapidly, and with it the demand for relatively low power chargers and also for higher power rapid chargers. Therefore, there will be increasing industrial capacity for these units by the time the HGV demand increases.

However, there is a possibility that the demand for this type of charger from other transport sectors will be very high and this will lead to constrained supply. Additionally, the depot chargers for articulated HGVs are likely to have a power demand >50kW (and have been modelled as such in this work) – since these chargers provide a DC power supply, their cost is higher per kW and they require more extensive planning and ground work operations. The potential rate limitation of depot chargers such as these would arise from grid / network power constraints. This is particularly the case due to the likelihood that these chargers would be clustered together due to the nature of HGV operations. Having multiple high-powered depot chargers would almost certainly lead to a need for network upgrades adding additional cost and delay. However, this clustering of chargers may enable many locations to benefit from a single network upgrade, where multiple upgrades would otherwise be needed

It should be noted that the scenarios developed for this analysis are (intentionally) very ambitious, requiring rapid and specific transitions to new technologies. This would be challenging in practice as such scenarios would require the wide-ranging development and deployment / availability of relevant ultra-low powertrain HGV models across all major market segments in <10 years. This should therefore be seen in the context of being an intentionally ambitious report, an assessment of infrastructure requirements should the vehicle manufacturing capability and market demand exist to enable decarbonisation of the HGV fleet by 2060, and not a forecast of expected changes.

8.1.2 Vehicle availability / readiness

The minimum charging time of a battery depends on the charger power rating and the battery capacity. This is a simple consideration of the time over which the required amount of energy can accumulate in the battery at a given power. For example, if a charging power of 10kW is used, 10kWh of energy will be accumulated in 1hr, 20kWh in 2hrs etc. However, as the power rate increases, further limitations become relevant dependant on the power capability of the electronics within the battery pack, the electrochemistry within the battery cells and the thermal management of the battery pack. Charging rate (C-rate) is limited in most batteries to 2C and in reality, regular charging should not be done at >1C in order to avoid battery damage (e.g. 500kWh battery should not be charged at more than 500kW power on a regular basis, although it could tolerate charging rates at 1MW for occasional, short charging events). Limitations also exist with respect to available battery capacity, minimising the depth of discharge and using high power at near full charge. Therefore, most batteries have a window of around 20% SoC to 80% SoC where high power can be used.

In this model, the available mass for batteries was calculated from data on ICE truck component weights (and their substitution by electric or hydrogen powertrain equivalents), the payload capacity characteristics and the gross vehicle weight limits. This was then used to calculate the potential energy storage capacity available within each vehicle class. The results of the analysis showed that – assuming no change in payload capacity – the available mass / space for energy storage was largely well below that implied by the battery capacities seen in current and announced electric HGVs (e.g. Tesla and Nikola). For this reason, it may be concluded that HGV designers could have a degree of freedom in design and have been able to streamline components to efficiently incorporate batteries, fuel cell components and hydrogen storage tanks with only some compromises to the vehicle's payload capacity / utility. As the energy density for batteries is expected to rise in coming years, the potential maximum (kWh) storage capacity will also increase. It is unclear how future improvements might balance between regaining payload capacity of current models or improving operational electric range. This will likely depend on the required duty cycle/characteristics of particular operators (already a range of battery sizes is being offered in newly released electric HGV models, reflecting this).

A further key consideration that is not covered by this analysis is the availability and cost of ZE HGVs in the widely diverse truck body configurations / specifications (as there are many types of non-standard HGV – such as waste collection vehicles, tippers, etc.) necessary to meet the fleet uptake trajectories assessed. This is clearly highly uncertain. It is clear that battery technologies will continue to evolve and reduce in cost due to their uptake in light duty vehicles (the rate and degree is less certain), and pantograph / catenary systems are a relatively mature/known technology. However, it is increasingly unlikely that hydrogen will provide a significant role in light duty vehicles in the foreseeable future, and without scale application there, technical development, cost reduction and availability are likely to be significantly slower than previously forecast for EVs. There is therefore a higher risk in terms of the timely availability of such vehicles to fulfil the deployment objectives. Further work beyond this project is therefore clearly needed to carry out an integrated analysis across the vehicle, fuel, grid power supply and infrastructure considerations.

8.1.3 Foreign HGV considerations

A range of stakeholders were consulted to assess the effects of mainland Europe and Ireland selecting a different zero emission HGV technology / policy than the UK. Stakeholders generally agreed that it is important to ensure a standardised / common approach to selected technology and policy between the UK and Europe, and that there should be a coordination role between the UK and Europe to ensure this takes place. It was also noted that all vehicle manufacturers will continue to lobby for their own technologies to be considered, in which case they may expect UK and European governments to adopt multiple infrastructure solutions (although this may not be optimal from a system perspective).

With respect to specific powertrain technologies, it was mentioned that the UK choosing battery electric or hydrogen HGVs and Europe choosing another technology would be range-limiting, whilst the UK choosing ERS and Europe choosing another technology could be range-prohibitive. As an example, if the UK chooses ultra-rapid charge points and there are no ultra-rapid charge points in Europe, then a UK HGV can only go as far as the battery capacity it has. If supporting ERS infrastructure is not available for ERS-enabled vehicles, then this greatly restricts the range of these vehicles due to the smaller achievable ranges without ERS infrastructure.

If the UK and Europe chose differing technologies, this would also necessitate more infrastructure at entry points to the UK and Europe to enable trailer swapping; this may require operators to have extra vehicles in both the UK and Europe, which could be cost-prohibitive. Questions also arise with respect to where the vehicles would be stored and how they would be accessed. One potential advantage of this was noted, with respect to the fact that all HGVs driven in the UK would be UK-registered, which would be advantageous for recording the vehicles in use.

8.2 ERS specific considerations

The deployment of ERS is estimated on a different basis than for HRS or ultra-rapid charging infrastructure (as summarised earlier in Section 6). ERS infrastructure is dispersed over a range of roads based on how intensively they are used by HGVs. It is assumed that 100% take-up of HGVs using ERS would require 100% coverage of the motorway network (and potentially also some multiple carriageway A-roads for BEV-ERS). In this work we estimate that 3,600km of ERS infrastructure will be required by 2050 under the Bat-ERS scenario. Of this, around 2,600km are motorway and 1,000km are A-roads. This then accounts for 80% of vehicle km on motorways and 13% of traffic on A-roads (however, due to higher proportion of articulated vehicle traffic on major A-roads the proportion of articulated vehicle km covered by ERS on A-roads is 21%).

It should be noted that a hybrid scenario with ERS and ultra-rapid chargers as an alternative could potentially lead to lower infrastructure costs than either scenario individually. This may allow for more targeted ERS infrastructure on a smaller proportion of roads which have higher HGV traffic, together with an ultra-rapid charger network which would be lower than that in the Battery scenario. Further work would need to be carried out to assess the optimal trade-off between these. Furthermore, it is worth emphasising that the current modelling assumes that the most intensively used roads have ERS added first. However, the practicalities of this and actual optimal geographical distribution of deployment may be different and would clearly require careful consideration with more detailed analysis and advanced planning.

8.3 Diesel infrastructure maintenance comparison

The costs of replacing and maintaining the existing diesel refuelling network have not been directly calculated in this project due to lack of data, although the potential numbers of refuelling points have been estimated based on a similar methodology to hydrogen stations.

However, the potential impact of factoring in these costs is likely to have a negligible impact on the overall findings for this analysis for a number of reasons:

- Diesel refuelling infrastructure is already established, mature and has a long lifetime, with infrequent refurbishment/replacements required. The costs of new / replacement equipment are (though not specifically known) significantly below those of hydrogen refuelling stations. In addition, previous analysis of infrastructure costs for alternatively fuelled vehicles and also for this study has shown that the infrastructure costs for new fuels/electricity are a small overall proportion of the overall cost/price of the supplied fuels.
- Outside of the motorway service station network, most refuelling stations are also shared with light duty vehicles, at the very least for small-medium HGVs, which makes it difficult to assess their costs separately.
- Due to market actions, costs of providing conventional refuelling stations are already included within the prices for petrol and diesel fuel. Because projections for future fuel prices don't typically separate out this component, separately accounting for them could introduce double-counting.
- According to the stock modelling calculations, relatively little replacement equipment is required over the period of the analysis for the ZEV uptake scenarios, and only modest replacement for the baseline. The former is in part also due to the significantly reduced requirements for diesel fuelling resulting from ZE HGV uptake – i.e. the infrastructure can mostly be run down as a result.

9 Conclusion

In this work, completed for CCC, Ricardo has created a model of UK HGV infrastructure. This has allowed for the simulation of a number of scenarios each intended to decarbonise road freight transport by 2060. The scenarios examined focused on a concerted shift towards a given technology, taking place over the period 2020-2050, with 99% decarbonisation of the fleet by 2060 (noting this is later than 2050 due to the long lifetimes of HGVs adding time for older models to be taken out of service).

Comparison of the scenarios enabled the following conclusions to be made:

- All scenarios considered, that achieve zero emission by 2060, are cheaper than the baseline (100% reliance on diesel) when fuel costs are considered, despite the large investments needed in new infrastructure. The magnitude of this saving varies by scenario between £1.54 bn/year to £1.37 bn/year in 2050 for Battery and Bat-ERS scenario respectively.
- A shift towards a hydrogen-fuelled HGV industry in the UK leads to the lowest overall infrastructure costs amongst the scenarios considered. The overall cumulative CAPEX cost for the hydrogen scenario is £7.67 bn by 2060, roughly 6 times lower than the costs expected for the battery electric infrastructure.
- The fuel costs and overall energy demand are lowest for the electric scenario; this offsets the higher infrastructure costs compared to the hydrogen scenario to make the Battery scenario the lowest cost option after 2050.
- Similar costs are predicted for all forms of electric infrastructure (ERS and Ultra-Rapid chargers). In both scenarios, at least 50% of the CAPEX costs are due to depot chargers (in fact it is around 90% for the Battery scenario). In many cases, these have a power rating >50kW and therefore DC charging technology must be used. This leads to higher costs per depot charger and reduces the cost competitiveness of the electric scenarios.

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Appendices

Appendix 1 – Full results of stakeholder engagement

Appendix 2 – Breakdown of component weights by different HGV size class

Appendix 3 – Market shares of HGV powertrains used within scenarios

Appendix 4 – Tabulated results of infrastructure cost and requirement modelling

A1 Appendix 1 – Full results of stakeholder engagement

This appendix provides the full results from the stakeholder engagement exercise undertaken as part of this project. The main results have previously been presented in Section 3; this section provides supplementary information from stakeholders that was not reported in the main report. The information presented below is paraphrasing stakeholder views and is collated and divided into responses based on specific topics.

A1.1 Infrastructure suppliers / manufacturers

A1.1.1 Hydrogen refuelling stations

Information obtained from stakeholders presented in this section is divided into the following categories:

- Capital costs of hydrogen refuelling stations
- Operational costs of hydrogen refuelling stations
- Evolution of costs and future reduction potential
- Lifetime / payback periods for hydrogen refuelling stations
- Challenges around deploying and operating hydrogen refuelling stations
- Minimum power requirements for hydrogen refuelling stations
- Refuelling capacities & behaviours at hydrogen refuelling stations
- Infrastructure build rate limitations
- Hydrogen vehicle considerations
- Additional considerations.

Capital costs of hydrogen refuelling stations

- For capital costs of HRSs, there is a large range depending on the source of the hydrogen. If a station is running on grey hydrogen (steam methane reforming, SMR) then it's a lower cost than blue (carbon capture and storage, CCS) or green hydrogen (electrolysis).
- The capital cost of an HRS is significantly higher than traditional retail site implementation; government intervention may be required for subsidies over a fixed period of time to incentivise the industry to get towards cost parity.
- There is an opportunity to build HRSs as a fuelling hub to introduce optionality for the hydrogen (i.e. blend it into the gas grid) – opportunity to consider both heat and power.
- Stations with electrolysers have a short supply chain, and the electrolyser is the major part of the cost. There is no orthodox supply of hydrogen yet; but if upstream elements are considered, tube trailers are a relatively small part of the costs. Clean-up / offtake of hydrogen is relatively easy, so it's a relatively small element of capital.
- The major parts of the capital cost breakdown are storage, compression and dispensing. Large scale storage is still in relative infancy – compression up to 700bar is expensive.
- Dispensers are off-the-shelf and are a relatively small component of capital costs (and the costs of these are expected to reduce), so the main elements are storage and compression – these are the costs that need to come down.
- The civil engineering and installation are relatively straightforward for HRS installation (however, if an electrolyser is included, an electrical power upgrade would be required, but this could cater for both BEVs and hydrogen vehicles). One of the biggest queries is with

respect to where to put the storage – some suppliers are looking into underground storage for large-scale storage.

Operational costs of hydrogen refuelling stations

- The operational costs (i.e. the costs of operating the station itself, such as payment mechanisms and upkeep) can be considered to be the same as a conventional refuelling site. Once the HRS is in the ground and in operation, the software is the same as a normal retail site and it has the same payment mechanism; gas rather than liquid, but similar costs.
- Once the infrastructure is down, parity is pretty much already there; however, the skills can be considered to be the outlier.

Evolution of costs and future reduction potential

- According to the stakeholders engaged, the hydrogen industry consensus is: if the hydrogen industry isn't at cost parity by 2030, then the technology may not be viable. 2050 was noted as being a long time to get to cost parity, and hence 2030 is the aim.
- Key dates in the hydrogen industry include: 2020, 2025, 2030. By 2020, the rollout of hydrogen vehicles should start to increase (LDVs, HDVs); 2025 = rollout of infrastructure should accelerate; 2030 = hydrogen economy of sorts up and running in some countries (e.g. Japan, Korea, China).
- No major developments in the operational costs of HRSs are expected, as they are already considered to be at parity. It was stated that there is a small gap to close with respect to the operational costs, but it is expected that this can be closed via a software upgrade.
- The uptake of expertise is expected to be the main cost to roll out the infrastructure. Big market players are currently doing the installations; there is a need to upskill the workforce, which would be the main installation cost.
- For HRSs, future reduction potential of costs depends on the source of hydrogen. Electrolysis is potentially one uncertainty – whilst it is on a cost reduction programme, there's no timeline for parity. Upstream electricity going into the electrolyser costs a lot of money. Two uncertainties: hardware, and policy for regulating electricity needed for hydrogen production.
- Another uncertain component is the storage element, i.e. how to get storage at scale and where to put it; is the fuel pressurised gas or liquid hydrogen; the compression piece is dependent on how many market players there are and the associated cost reductions.
- Uncertainty for vehicle choice was highlighted as a concern – there doesn't appear to be a consensus in the HGV market with respect to where the market is going. There is no coherence in the heavy-duty market on what the solution(s) might be, particularly when considering differing powertrain types and HGV sizes. The lack of consensus makes infrastructure supply more difficult.
- There is no consensus on vehicle operations either – e.g. no consensus on how to charge the vehicles.
- Capital expenditure is expected to be significantly higher than for standard trucks. Breakeven point is highly dependent on H2 fuel prices.

Lifetime / payback periods for hydrogen refuelling stations

- The lifetime of an HRS can be considered to be the same as a conventional site – they are refreshed every 10 years. All sites are using conventional sites as benchmarks.
- The payback period depends on the policy makers – a good incentivisation policy can enable the market pretty quickly. The main aim is for the payback period for hydrogen to be the same

as for a liquid site, but it also varies company to company, depending on who owns the station. Stakeholders did not comment on what a "sensible" payback period was, as this information is still considered commercially sensitive.

- For maintenance and servicing, infrastructure operators want something similar to liquid fuel stations, as a benchmark. Low utilisation of infrastructure is considered a problem, as the station is idle; higher utilisation leads to problems being identified, which can then be learned from in terms of future rollout of infrastructure.

Challenges around deploying and operating hydrogen refuelling stations

- The longest lead time is the planning and permitting process. If a well-established book is used (e.g. Blue Book) for planning new builds, this can be effective, and can also help with health and safety requirements. Every council has a different planning policy, and different restrictions operating in and out of a city. Typically, the planning and permitting process is the major barrier. Stakeholders indicated that three months comprises a typical planning period, though this can vary depending on how informed a council is on hydrogen transport.
- Doing a lot of work upfront is usually beneficial – e.g. engaging authorities long before the planning application goes in. A lot of towns and cities are very well aware of the benefits of hydrogen; but there can be an educational piece for new cities
- There shouldn't be any supply chain issues – electrolysis has a very short supply chain. One barrier for tube trailers is that there are individual city restrictions on driving them through cities. There may also be restrictions on driving hydrogen around in a diesel truck. Practical applications around supply chain need to be considered.
    - **Ricardo comment**: the availability of hydrogen in volumes needed to support mass transition of the HGV fleet must also be considered. For recent examples in the UK, hydrogen had to be imported from the Netherlands using diesel barges.
- Pipeline is used in the US to supply infrastructure sites; some discussions have begun in the UK to do the same, but there is a tie-up of volume vs. cost.
- Site identification is normally driven by the site itself (some operators can add to existing sites). There needs to be a step change towards integrated sites for new sites (liquid and gas).
- Standalone sites for both hydrogen and e-mobility may emerge as an option, e.g. a dedicated hydrogen site with a dedicated fleet of vehicles that a company is committed to. Standalone sites need to be anchored to an assured demand, which is very well-suited to HGV and bus fleets.

Minimum power requirements for hydrogen refuelling stations

- The minimum power requirement depends on the source of hydrogen – for an electrolyser site of 200kg per day, a 1MW power source is required. This increase linearly – 10MW would be required for an electrolysis station producing 10x the hydrogen.
- Tube trailers require a small power upgrade for compression and dispensing, but not much more than a standard retail site. A rough estimate is 50% extra power on top of a standard retail site.
- If the retail site has 20 dispensers but one hydrogen station, then the compression and storage will have an add-on to the power requirement, but only by approximately 25%. This power requirement increases as more dispensers are installed. The power requirements are likely to come down as storage and compression capabilities improve.
- Power requirement is fully dependent on how much hydrogen is intended to be produced per day, and on compression and storage requirements.

Refuelling capacities & behaviours at hydrogen refuelling stations

- The number of HGVs that can be supported by an HRS is linked to demand. If every truck going through is filled once per day, they're likely taking 8-10kg of hydrogen per fill. As such, 100 trucks would consume 1 tonne per day, which would be a sizable station.
    - **Ricardo comment**: this view appears based on existing vehicles sizes and refuelling habits, where the tanks are smaller, and drivers are not fully refuelling their vehicles. The vehicle sizes within the current study are far in excess of the 10kg of refuelling stated here.
- The number of tricks that can be supported by an HRS is limited by the ability to make a large amount of hydrogen. The limit of a tube trailer is approximately half a tonne – as such, it is a question of large electrolysers vs. more tube trailers.
- For number of dispensers, 100 trucks per day would require 4-6 dispensers; the question becomes whether there would be redundancy on the compression. The limiting factor is the ability to store and produce hydrogen at a particular site, which limits the amount of trucks that can be serviced.
- Hydrogen refuelling occurs at approximately 1kg per minute. An HGV will typically take 10-12kg, and a car typically takes 1-5kg currently – the time is similar to a liquid refuelling site.
    - **Ricardo comment**: some larger HGVs have much larger tanks, which could mean far longer refuelling times that are greatly in excess of diesel refuelling times.
- The 1kg per minute refuelling time is expected to improve as metering / dispensing / compression gets better.
- Throughput is linked to demand – currently, an HRS does about 5-10 refills per day at one pump, but a liquid fuel site can do 4,000 refuels per day. Infrastructure operators have the know-how to deploy the infrastructure; but they need the demand in place. They are now ready to commercialise hydrogen.
- The freight industry should be consulted more widely to see how refuelling fits with their operations, but it was noted that HGVs are more relaxed with respect to refuelling times for liquid fuels.
- 350bar and 700bar refuelling have approximately the same refilling time. There's discussion ongoing on whether the HGV industry needs something different – 700bar needs to be cooled before it's dispensed, but 350bar doesn't. 700bar is well-established for LDVs.

Infrastructure build rate limitations

- Build rate limitations are more about skills than the time taken to construct. The complete construction time is 12-18 months but planning and permitting is the frontloading that takes time. Total construction: 3 months permits; 6-9 months constructing; 6-9 months civil engineering. This can be considered standard into the future.
- Construction time is relatively constant; the timeframe either side is as long as the planning / permitting process takes.
- Timespan for construction depends on the local authority – frontloading reduces this time. Site identification can currently be dependent on subsidies – infrastructure operators have to decide as a consortium where the demand is going to be.
- HGVs could have dedicated infrastructure for the industry, with individual refuelling areas for that and similar industries; or could look to set up additional stations at MSAs. Infrastructure operators are looking at existing portfolios of sites, and whether they're standalone stations, which would have to be large enough to serve an anchored demand.

- Skills and upskilling of the workforce can be considered the main limiting factors; however, the H2 Mobility Germany project has incorporated a build rate model seeking to deploy 400 HRS sites between now and 2023.
- Some hardware components can also be a limiting factor, such as compressors.
- There is probably a maximum amount of stations that can be deployed per year; but it's likely a lot more than people realise.
- There could be a paradigm shift if one market becomes very active in the hydrogen deployment space (e.g. breakthrough on compressor manufacture).

Hydrogen vehicle considerations

- With respect to storage limitations, for articulated vehicles there is a trade-off between how much fuel is in the truck vs. the range. Most HGVs are 1,000L capacity; with hydrogen, there is a restriction with respect to how much fuel can be on the truck, particularly for 350bar refuelling.
- The length of the HGVs restricts the hydrogen storage capacity. There's a discussion over increasing the length vs increasing the pressure (to 500 bar).
- There are ongoing discussions regarding liquid vs. gas hydrogen storage – liquid hydrogen has been discussed by some manufacturers.
- Vehicles are getting very close to range parity now for LDVs – they have a range of around 700km already on hydrogen, which is parity with diesel. However, there may need to be a subtle change in behaviour with respect to how fleets operate.
- Fleets may need to modify how they refuel and have slight additional training; and the long-haul industry may need to refuel slightly more frequently, but not by much.

Additional considerations

- One opinion is that hydrogen represents very good opportunities long-term in long haul, but it has good short-term prospects are more focused on last mile deliveries etc.
- Infrastructure operators want something as convenient as they have today, and they want it at the same price. Regulatory help for hydrogen will enable them to be rolled out all the way up to the heavies.
- Message to give back to policy makers: infrastructure operators are committed to commercialising hydrogen, but they need a policy that helps them enable it. There needs to be incentives in place, and they need to be time-based. Infrastructure operators would like to talk to policy makers about this – a different approach to incentivising is required.

A1.1.2 Charging infrastructure

Information obtained from stakeholders presented in this section is divided into the following categories:

- Capital costs of charging infrastructure
- Additional costs of ultra rapid chargers
- Charging infrastructure requirements
- Charging infrastructure build rate limitations
- Limiting factors to deployment of ultra rapid charge points.

Capital costs of charging infrastructure

- Capital costs of higher-powered charge points are commercially sensitive. A significant proportion of the cost goes towards power upgrades. A small number of sites have spare capacity for 50kW charge points, but there is a need to apply for an upgrade for the majority of sites, which produces mass variability.
- For 150kW charge points, there will always be a need to pay for upgrades, but there is a chance of small upgrade costs (~10% chance) for 50kW charge points. Upgrade costs are not the main share of capital costs for 150kW charge points, but they comprise a significant amount.
    - **Ricardo comment**: the DNO and civil costs should be linked, as they form the overall total upgrade costs.
- For 150kW charge points, DNOs have to build new substations. For 50kW charge points, there is an average of £10k per upgrade (considering all rapids, including those for which an upgrade is not required). Cost upgrades for 150kW charge points can be in the region of £100k; however, there is mass variability, and there is not a linear relationship between charger power and upgrade cost.
- 350kW charge points are not common yet – IONITY (the joint venture being led by German car manufacturers) are seeking to roll out 350kW charge points in the UK; however, there is no visibility on CAPEX costs.
- Current 150kW charge points are primarily intended for passenger vehicles, for longer trips and for those without access to domestic infrastructure.
- The main components of the capital costs can be considered to be the hardware, DNO connection, power upgrade, and commissioning.
- The hardware costs of infrastructure can be considered to be a roughly linear relationship – i.e. cost of hardware for 150kW = 3x cost of hardware of a 50kW [two stakeholders supported this assumed relationship].
- The majority of the electrical components sit in a separate box than the charge point infrastructure, hence the increased costs – cooling equipment is required to be implemented for higher-powered chargers.
- There is a much stronger correlation between existing power infrastructure and cost. More power requires more cost on average, but because of variability in the cost of upgrade, it’s more about the site itself and the upgrade requirement.

Additional costs of ultra rapid chargers

- Civil costs can also be quite considerable – e.g. digging up forecourts for electrical connections if they are located at MSAs and relaying the forecourts. Other costs include branding, lighting, CCTV, and electrical safety costs. The hardware needs to be wired into an emergency stop on a forecourt, which can increase the costs. Charge points must also not be located in “hazard zones” around existing refuelling dispensers, which limits their positioning.
- The installation costs of ultra rapid charge points are also commercially sensitive; however, similar to the cost of hardware, an assumed linear relationship between charger power and the cost of installation can be considered to be roughly valid and is supported by stakeholders.
- For operational costs, there are lots of business models to choose from, and some infrastructure suppliers have outsourced the operation of higher-powered charge points to companies that provide an all-in-one service (e.g. software, support, maintenance, project management, apps, etc.).

- The operational costs of ultra rapid charge points are also considered to be currently commercially sensitive.
- With respect to potential reductions in costs, one stakeholder does not foresee any substantial changes in hardware costs – the technology is not considered ground-breaking, so there may not be large reductions. Efficiency improvements may lead to reduced costs.
- One area where cost reductions may happen is DNO power upgrades. The utility costs are considered the main uncertainty (i.e. the cost of energy).
    - **Ricardo comment**: as previously stated, DNO / power upgrade costs are not included in the CAPEX in the modelling for this study but are explored using a sensitivity analysis.
- One stakeholder supported applying a learning factor of 0.9 for CAPEX and 0.98 for installation within the modelling in this study.

Charging infrastructure requirements

- Infrastructure suppliers are keen to ensure all customers can use the infrastructure with respect to charge point connections – preference shown for making them downwards compatible.
- There are queries over IONITY and the possible plans to enable connections to top-end cars only, and not making them downwards compatible with Japanese-manufactured EVs.
- Infrastructure operators plan to react to the market and to customer demand in their assessment of whether ultra rapid charge points will be necessary,
- The charging time / recharge delivery rate of charge points can be considered to be directly proportional to their power – e.g. 6-7 minutes for the 150kW to achieve 80% battery state of charge (SOC); 2-3 minutes for the 350kW to achieve 80% SOC; etc. This is also dependent on the duty cycle of each vehicles, and the remaining SOC in a battery prior to a charge event.
    - **Ricardo comment**: the time taken to charge also heavily depends on battery size.

Charging infrastructure build rate limitations

- 150kW charge points would take one week to install, on the premise that the infrastructure is already in place (such as power upgrades & DNO connections). 350kW charge points take slightly longer to install – a few weeks rather than one week.
- Substation upgrades take far longer – this is dependent on the DNO and requires agreements to be in place (e.g. wayleaves), which can take a long time to process.
- The majority of the mass variability is driven by the power upgrade requirement. If there's no upgrade requirement then this is a very short time span.
- It takes 6 months plus, on average, for the DNO upgrade to be in place – this includes civils on site (which is not considered to be too onerous). Depending on the size of the charge point post, planning permission may be required, which also involves a 12-week lead.
- The hardware for ultra rapid charge points are on a 6-8 week lead, depending on the supplier and the requirement for the infrastructure.
- DNO upgrades comprise the main challenge in terms of delays – from the infrastructure operator perspective, they have choice of multiple suppliers of infrastructure and multiple contractors for civils, but they do not have this choice for DNOs.

Limiting factors to deployment of ultra rapid charge points

- Local authorities approving planning permissions and DNO upgrades can cause delays, assuming there's funds available to install the infrastructure.
- One stakeholder noted that the challenge of installing ultra rapid chargers rises with size of installation primarily due to the cost of the grid connection. From experience rolling out a network of higher-powered charge points, the need to get a wayleave to lay cables across third party land is considered a major barrier (the wayleave is between the DNO and the land owner). It can delay projects for months or even over a year with no clear process or timelines. This applies any time chargers are being installed above the available power level at a given site. This is a major barrier to rollout of multiple ultra rapid chargers in the UK.
- The difficulties of wayleaves are also almost unique to the UK, which is considered by some suppliers to be one of the most difficult places to roll out charging infrastructure.

A1.1.3 Overhead catenary infrastructure

Information obtained from stakeholders presented in this section is divided into the following categories:

- Costs of ERS infrastructure
- Potential cost reductions of ERS infrastructure
- Servicing and maintenance
- Operations of ERS infrastructure
- Construction time per kilometre of ERS infrastructure
- Ownership of ERS infrastructure
- Main factors limiting further deployment of ERS infrastructure

Costs of ERS infrastructure

- The cost of the eHighways system funded by the Federal Ministry for the Environment, nature Conservation and Nuclear Safety in Germany is €14.6m for 5km in each direction = 10km in total; for capital costs, the client's project management work must be removed. Please note this is a field trial planned for a period of five years, and as such costs may vary depending on the number of trucks in a feeding section and topography of the motorway itself (slopes, curves) and access to public grid (distance to next grid's feed-in point). Standardization will help to save costs to a certain extent.
- The civil works and installation / grid connection costs depend on the nature of works needed to be performed – when energy is required for ERS, the question is: where is the feeding point and what there any cabling work involved? How much cable work is needed in terms of distance? What is the diameter of cabling? Copper of aluminium?
- The evolution of costs very much depends on the way it is financed. Public financing for a period up to 30 years may allow interest rates below 2%. Private financing is often linked to a 10-year period – higher interest rates due to credit worthiness and higher expectation of incoming cash flows.
- For operating costs for the infrastructure, this is tied to the development of energy prices, specifically price per kWh, network fees and usage / payments received per truck using the ERS.
- For vehicle operating costs, there are calculations that 1-2% of investment costs for the pantograph is to be considered in 2025.

Potential cost reductions of ERS infrastructure

- The prices for electric power in general are an uncertainty.
- The main infrastructure components are: development of substation, mast, and catenary wire costs.
- Siemens has a long-term record of reliable prices / suppliers and they expect some reductions due to standardization. This is similar for installation works for cabling and catenary system. However, for vehicles, Siemens expects significant savings, e.g. power electronics, battery and pantograph.
- For payback periods, this is very much dependent on the level of usage e.g. by freight forwarding companies, financing and regulations, policies set by governments, public authorities and motorway operators.

Servicing and maintenance

Assumptions used with respect to the servicing and maintenance of the infrastructure are as follows:

1. Preventive maintenance in place e.g. via remote maintenance by motorway operator's control centre
2. Regular maintenance works on site according to service plan every 12 months: cleaning dust from dry transformers, greasing MV switch gear, changing contacts from overhead wire laser remeasurement from special vehicle, exchange contacts of DC switch gear and visual inspection (foundations, masts).

Operations of ERS infrastructure

- Siemens has assessed the question of how many HGVs can be supported by the system based on real life conditions worldwide. Even the demand on a highway section like in the US (Southern California I-710) with approx. 20,000 trucks per day in each direction can be met – i.e. no limitation.
- The installation of the system depends on how many trucks are planned to be using the infrastructure, along with topography and payload in the HGVs
- Power infeed from grid network to substation is either at 20kV or 30kV AC, 50Hz (in Germany).
- Inside the substations, electrical power is transformed to 750V level DC and distributed via in-feeding mast to the feeding section (2-3 km in both directions).
- From catenary to pantograph, power transfer of approx. 600A is made (whilst driving).

Construction time per kilometre of ERS infrastructure

- 1 month / single km was achieved in both German field trials, which can be significantly accelerated by deploying extra construction personnel (e.g. two-shift-operation and more teams working at the same time). This is currently under assessment by Siemens Mobility and will always depend on the individual situation of respective motorway sections.
- Basic factors affecting construction time include:
    - conditions e.g. topography and traffic density of respective motorway;
    - regulations set by motorway operator (blocking times e.g. holiday season, night work bans, setting-up construction site e.g. temporary or permanent);
    - allowed length of construction site / limited access ways to construction site due to structures alongside the lanes e.g. noise barriers;

  - availability of trained installation personnel and special vehicles (for pulling the contact wire, telescopic crane for deploying the substations).
- For both German field trials, the time span from site identification to delivery was:
  - 6 months site identification
  - 6 months tendering (2 step-approach)
  - 9 months construction (incl. engineering and civil works)
  - 3 months commissioning

Ownership of ERS infrastructure

This depends on a political decision how motorways today and in future are intended to be managed:

1. Motorway operators, private- or state-owned (e.g. Highways England) or
2. Regional Government (e.g. province of a country) or
3. Network operator as private investor besides their role as supplier of energy to an ERS system or
4. Joint venture (e.g. motorway operator, ERS supplier, third party).

Ricardo comment: in the UK, Highways England contracts out concessions for motorway section operations.

Main factors limiting further deployment of ERS infrastructure

The main factors stakeholders consider are limiting the further deployment of ERS infrastructure can be considered to be as follows:

1. Taking the decision to implement an ERS system first on national level and to align / coordinate this among European countries
2. Inefficiency in terms of costs due to low level of usage and in terms of CO_2 reductions
3. Long distances from grid network to substation near the motorway, causing high costs on the grid operator side
4. Insufficient space for construction works on the motorway e.g. no break-down lane existing or no/limited access to site due to private property

A1.2 Road freight operators / trade associations

Information obtained from stakeholders presented in this section is divided into the following categories:

- Journey lengths of HGVs
- Operational considerations – geographic restrictions
- Refuelling habits of HGVs
- HGV characteristics
- Market shares of vehicle powertrains up to 2050
- Ultra rapid charging vs. depot charging for battery electric HGVs
- Storage limitations for zero emission powertrain HGVs
- Additional considerations / recommendations from road freight operators / trade associations.

Journey lengths of HGVs

- Associations gave support for using DfT data to estimate journey lengths.

- Commodities of HGVs are extremely important when it comes to determining journey lengths – different commodities have very different duty cycles (e.g. concrete mixers) – construction vehicles, mining vehicles, delivery vehicles, and refrigerated trucks should all be considered separately.

Operational considerations – geographic restrictions

- Road freight operators noted the difficulties of Clean Air Zones (CAZ) for fleets of vehicles – it was noted that CAZs can fast-track the fleet replacement cycle. This was also noted as being important for manufacturers – they don't have enough vehicles to be able to complete the orders. The importance of providing clear information on CAZs was also noted.
- Infrastructure costs would be extremely large if different infrastructures were required; however, varying vehicle commodities need to be considered.

Refuelling habits of HGVs

- Refuelling depends on operation – long-haul trucks will need to refuel on motorways, and this is dependent on when they take their breaks – this is dictated by the European Union rules on drivers' hours and working time.
- A lot of refuelling is carried out in home depots; drivers make use of fuelling cards outside of this refuelling behaviour. Local deliveries in smaller trucks will typically require vehicles to come back at night and not require en-route refuelling. Long-haul trips make use of fuel cards.
- Refuelling also depends on the need of the business. Daily refuelling would be very rare; but every 2-3 days refuelling is common, dependent on the commodity.
- Some vehicles can refuel during the day whilst others can't – HGVs should be divided into commodities rather than by sizes to account for this. There is no "one size fits all" solution similar to diesel that's available today.
- There will be a proportion of drivers for whom a vehicle will be idle at night; but it will be idle away from their depot. There are some vehicles that are manned all day every day, and as such they don't have time to refuel overnight (typically modern high-mileage articulated HGVs) – in this respect, support was given for a battery-assisted overhead catenary system on the motorway, as the vehicles are charging as they travel and have flexibility.
- It was noted that a system of overhead catenaries makes rational sense dealing with one kind of market (articulated) but doesn't make sense for those that don't go near a motorway / deliver to pubs or restaurants / construction vehicles, etc.

HGV characteristics

- Freight is very diverse so it's difficult to determine the minimum acceptable range of a zero-emission powertrain HGV. This depends on type of operation – long haul, urban delivery, multi-drop, etc.
- A small number of vehicles (typically articulated vehicles doing long haul trips) will be in use as much as feasibly possible, travelling upwards of 600 miles per day. Other vehicles (e.g. London delivery companies) could only do a 40-mile range. As such, range is entirely dependent on duty cycle and commodity.
- Road freight operators would like the DfT to record accurate statistics on payloads – the stated payload is dependent on how it is measured (e.g. volume, weight, etc.). Load factors and empty running are of concern to plenty of businesses.

Market shares of vehicle powertrains up to 2050

- Possibility was raised that gas could be used a bridge technology. Lighter HGVs and vans are well suited to be battery electric vehicles, but gas was highlighted as being a possible bridging technology until battery technology develops further. Research is currently ongoing to assess emissions from gas-powered HGVs.
- Conversely, there are a lot of industry opinions saying the HGV market should not be looking at gas, and that the focus should be on electric.
- One freight transport trade association questioned the role hydrogen will play in the market, as they are of the opinion it's quite inefficient when generating hydrogen, despite being zero emission at tailpipe.
- The importance of giving the industry certainty with respect to choice of technology was repeatedly noted. Academics are saying to look at electric (noting the technology won't develop fully unless there is a move towards that technology), but there's a lot of uncertainty in the industry with respect to which powertrain technology will "win".
- Support was given to carrying out trials of overhead catenaries for HGVs.
- Several freight operators invested in early generation gas trucks, which ended up being worse from an emissions standpoint than diesel – they are reluctant to take the investment leap again. As such, operators are waiting for emission results of second-generation trucks. There needs to be concrete evidence before trade associations provide support for a technology.
- The importance of an agreed definition of an Ultra Low Emission Truck was noted, as this will determine the immediate next generation of vehicles and also will shape future policies.
- One trade association noted the risk of getting ahead of the technology, and stressed that the technology may need to develop further for the various powertrain technology types before making a policy decision.

Ultra rapid charging vs. depot charging for battery electric HGVs

- The importance of looking at the operation was noted, and where the depot is located – e.g. UPS has a depot in Kentish Town where they are operating light electric HGVs with a back-to-depot model. They have enough range to travel around London and come back to charge; however, long haul operators on trunking roads may need additional charge points en route.
- Freight operators are talking about having to change their method of operations and planning journeys made in electric HGVs, such as where they're going, how far their depot is from the destination, etc. Operators might look at depot charging more at the beginning, but as public infrastructure develops, they might then move away from depot charging because they can rely on en route charging.
- A case study (Centre of Sustainable Road Freight) on buses was noted, which could be applied to freight vehicles. The study compared a heavy battery (depot charging) and lighter battery (opportunity charging) for charging behaviours and payback periods – the lighter battery was the better option for payback periods, with the lighter battery having a 14-year payback period, and the heavier battery having a payback period >14 years.
- With respect to charger power, it was noted that the freight industry will always prefer faster chargers, particularly as some vehicles are constantly in use.
- The importance of a definition of an Ultra Low Emission Truck was noted with respect to how fast charge points should be – it is difficult to comment on what type of charging infrastructure will be needed until this definition is specified. Charger power also greatly depends on what type of operations the vehicles are being used for.

Storage limitations for zero emission powertrain HGVs

- There was a recent derogation for 4.5 tonne vans – the government decided to bring in a derogation to allow drivers to drive more than 3.5t to allow for the weight increase in the battery. This can help encourage industry to move over to electric vehicles; however, government is still trying to figure out how to implement the derogation.
- As vehicles get heavier, more derogations will likely be implemented, but this will develop as the market subsequently develops.
- The weight of an alternative powertrain must not negatively impact payload – if operators are sacrificing payload due to an increased weight of the battery / fuel cell, this will increase the number of vehicles on the road and increase congestion which in turn will increase emissions.

Additional considerations / recommendations from road freight operators / trade associations

- The point was stressed that the freight industry can be exposed to unfair standards – CAZs are being brought in outside the rational vehicle replacement cycle. It is considered fundamental to base policies around the vehicle replacement cycle, when considering the year / time it would be achievable to have a fully zero emission HGV fleet.
- For a fully zero emission fleet by 2050, all new vehicles will have to be zero emission by 2035; as such. All decisions will have to be made within the next 6-10 years.
    - **Ricardo comment**: this can be compared with the scenario trajectories developed for the current study, where the uptake of zero emission technologies is assumed to greatly accelerate from around 2030 onwards.
- The importance of looking at specialist HGVs was noted, with respect to their unique requirements – it is unlikely there is a one-size-fits-all solution for zero emission powertrains.
- One freight trade association noted that the costs of the vehicles must be considered – whilst this study primarily focuses on the costs of infrastructure, the overall cost of operation must be looked at in its entirety, including vehicle costs.
- Policies developed outside of the existing vehicle lifecycle replacement can disproportionately affect and disadvantage SMEs – the natural replacement cycles of the vehicles must be considered and fully understood. Some lesser-used vehicles can last for 25 years.
- Whilst the government motivation on climate change is important, policies must consider the people and businesses doing the transition.
- Some concern was expressed regarding catenary systems and wires being pulled down, causing safety concerns on the motorways.

A1.3 Road owners / operators

Information obtained from stakeholders presented in this section is divided into the following categories:

- Operational considerations – battery electric HGVs
- Operational considerations – hydrogen HGVs
- Operational considerations – ERS HGVs
- Foreign HGVs with different zero emission technology coming into the UK
- Road closures required to install ERS infrastructure
- Cost of road closures.

Operational considerations – battery electric HGVs

- The only barrier envisaged for highway operators is when an HGV runs out of charge. When battery electric HGVs are on the network, there is a question over how to recover them, particularly in an area where there is no hard shoulder. Recovery fleets may need to be enabled with recharging infrastructure, which may involve reequipping the recovery fleet.
- Mitigation against electric HGVs breaking down would be high frequency of charging stations on the network. For example, on the M25, there's quite a distance between MSAs so the opportunity to top up the charge is infrequent. Land could be allocated for HGV recharging on the highway.
- The EU drivers' law currently states that drivers need to take a break every 4 hours. It was noted that this legislation should be considered for deployment of new technologies. For example, a 200km journey between charging opportunities (50 km/h for 4 hours) may be undertaken before the driver requires a break.

Operational considerations – hydrogen HGVs

- Similar to electric HGVs, there's no additional draw on physical infrastructure for highway operators; rather it's how they manage and assist vehicles powered by hydrogen, such as vehicle refuelling and breakdowns. Range of hydrogen vehicles is important to road operators.
- Incident response is important to highway operators also- there is a query over whether an incident involving a hydrogen vehicle would have a greater impact than a fossil fuel vehicle (e.g. if a fuel cell is ruptured). Highway operators know how to deal with fossil fuel fires, but not with a hydrogen incident.
- Minimum infrastructure requirement is very important to highways operators, and also incident response, such as recovering broken down vehicles and possibly reequipping their fleet to carry hydrogen fuel. Adequate infrastructure provision for HGVs is seen as being vital.

Operational considerations – ERS HGVs

- Each gantry supporting the catenary system would be considered a structure under Highways England standards. There are strict regulatory requirements for these, and the lane would need to be closed to carry out physical inspections (the catenary systems are lightweight and wouldn't be able to support a walkway). The inspections would need to take place every two years, for every single gantry. Resourcing to carry out the inspections was highlighted as a very serious issue, to the point it would be infeasible.
- One stakeholder noted an issue with respect to the heights of HGVs and over-height vehicles – whilst it's rare that HGVs have heights above a limit of just over 5m, larger vehicles do exist, which could potentially cause lane availability and congestion issues. A query was raised over whether ERS could increase the likelihood of incidence.
- If HGVs were confined to one lane with overhead infrastructure, it would make the lives of road owners and operators easier. Lanes would need to be closed for inspection or routine maintenance, so the HGVs would have to be equipped with an alternative power source.
- Road owners and operators would need to consider how they manage their maintenance activities – there are very short work windows, and they would need to be as efficient as possible whilst working with diggers, cranes, etc. whilst installing the infrastructure.
- There is a lot of congestion on UK motorways – deploying infrastructure on motorways is very challenging in terms of construction works. This is particularly true as the majority of infrastructure installations are on existing infrastructure sites, rather than greenfield sites.

- As a road operator, the first question is about the impact on traffic – penalties occur between 6am and 10pm for lane closures, which are paid to the grantor (Highways England). Construction work would need to be carried out at night time, which is a big constraint from an operational perspective.
- A strong knowledge of the utilities in an area where ERS is being installed was deemed to be essential. Road operators have noted a lot of difficulties working with utilities to deploy infrastructure, and a lot of administration work is involved. As such, testing ground for initial pilots should be very carefully selected.
- Consideration should also be given to dangerous goods vehicles (DGV) – they can't use some types of road infrastructure.

Foreign HGVs with different zero emission technology coming into the UK

We asked numerous stakeholders on their views of foreign HGVs with differing zero emission powertrains coming into the UK than the option chosen in the UK, and operational issues that could arise from this. The following table highlights the views of different stakeholders on this issue.

No.	Stakeholder Views
1	• Other HGVs would be range-limited, particularly if the UK (or Europe) opts for ERS. Would be range-limiting for battery / hydrogen; and range prohibitive for ERS. • HGVs may need to swap trailers at an entry point to the UK (e.g. Dover). From an operator point of view, this would be advantageous, as tractor units would be UK-registered, which could assist with day-to-day housekeeping. However, a lot more infrastructure would be required at entry points, and every logistics operator would need a fleet on either side of the Channel. • Someone should take responsibility for ensuring the UK's solution is aligned with all if not the majority of Europe. Anything arriving by air / sea needs to be compatible. DfT was highlighted as being potentially suitable for this role – it needs to be applicable to both the strategic and local road network; and it's DfT that sanctions and funds infrastructure in the UK. • Tunnels and vehicle ferries may also prove to be problematic.
2	• This is not an issue – manufacturers will lobby for interoperability of the network. Irrespective of the technology that's chosen as being prominent in either the UK or Europe, manufacturers will ensure their vehicles are included. • Used the tolling industry as a comparative example.
3	• If every UK truck is required to be 100% zero emission, and non-zero emission foreign trucks are allowed into the UK, then the UK haulage industry is being put at a disadvantage. This needs to be done on a Europe-wide basis. International road haulage may not be able to be zero emission. • Need to consider how the markets behave – the differences in neighbouring countries need to be assessed and considered. • International cooperation is vital to ensuring interoperability – possibility of setting up a pan-European body.
4	• Flows are highly interconnected within Europe – it is totally crucial to set up a system in such a way that it is interoperable between European states (geographical Europe). Interoperability would be highly desirable despite Brexit.

No.	Stakeholder Views
	• Railroad is a negative example – there are different catenary systems, and different pantographs on the rooves of trains. European bodies should be responsible to set up coherent standards for interoperability – these tend to be driven by industry. Minimum standards should be set for the whole of Europe, and government should work with industry. • There should be a coordination role for Europe / the UK.

Road closures required to install ERS infrastructure

- At least two lanes would need to be closed for every installation. This would have to be undertaken as night work over multiple nights, unless contraflow is initiated, which would be for a major project (also involving speed reduction). Slip roads would also need to be closed if installing infrastructure across the slips, unless the catenary system allows for breaks – closing slip roads would have to be night work. From a user / operational perspective, having catenary wires going across slip roads whilst having vehicles going underneath may be problematic.
- Duration of installations depends on construction requirements – if it's similar to a variable message gantry, then it's a matter of carrying out the civil works, fitting the structure and commissioning the technology. This would involve a minimum of four visits per gantry, but this would not be over consecutive nights – the concrete would need to cure, as an example.
- Operationally, road operators tend to be limited to 4km of length of lane closure. If installing ERS, operators could install as much as feasible within that 4km. For contraflow projects (e.g. smart motorway), this can be carried out during the day, and the length limit increases to 10km.
- Gaps of 10km between lane closures must be maintained, but operators would not want to go 10km on, 10km off – this would make the scheme very unpopular very quickly. Logistically, operators would struggle to find a contractor with enough resource to do more than one 10km closure.
- For efficiency, installation would be better under contraflow as a major project. The power requirements for the electrical infrastructure must also be considered.
- Queries were raised over ownership of the infrastructure and who provides the power to the vehicles, and how they get paid for providing that power – Highways England may be resistant to becoming an energy provider. One opinion was that the energy provider should fund the infrastructure as they would be paid by the users to provide the energy. If the energy provider supplies the infrastructure, it's a transaction between supplier and user.
- Lane closures need to be booked a year in advance – road operators have their own schedule of road closures for routine maintenance, and efforts could be made to align the road closures. On a related note, it is important to phase the installations with renewals of pavements, and to align the two. Highways England is aware of their repairs schedule, and it could be phased with an existing lifecycle programme to optimise for cost and disturbance.
- Security of assets must also be considered, such as signage, posts, fibre optic cables, etc. Catenary systems also need to satisfy safety standards.
- In both German field trials, civil works (cabling, foundations, erection of masts) were made using the emergency lane which means no interference with traffic. For installation of catenary wires, temporary closures during times of reduced traffic were necessary.

Cost of road closures

- An approximate cost for 4km of road closure = £2,000 per night. These costs would be higher for contraflow projects, but information on the costs for contraflow projects was unavailable. The £2,000 would be purely for traffic management rather than for the infrastructure.
- Road closure costs depend on what time it is. Penalty schemes are in place, and there may be large costs associated with installations depending on the time they are undertaken.
- Highways England is the grantor, on behalf of the Office of Rail and Road, and thus determines and collects the penalties. One lane closure could be approximately £5,000 depending on the time of the night, the day of the week and the location of the closure.
- Some sample road closure penalties are as follows:
  - 3 lanes closed on a Monday morning for one hour, with a 50mph speed limit: £18,314.
  - 2 lanes closed on a Monday morning for one hour, with a 50mph speed limit: £10,391.

A1.4 Current ERS infrastructure operators

Information obtained from stakeholders presented in this section is divided into the following categories:

- Cost and lifetime of ERS infrastructure
- Operational challenges around deploying and operating ERS infrastructure
- ERS infrastructure build rate limitations
- Opinions on ownership of ERS infrastructure / how it’s funded
- Main limiting factors to further ERS deployment beyond trials.

Cost and lifetime of ERS infrastructure

- The payback period depends heavily on the usage intensity. Therefore, it would be expected to decrease with ongoing market uptake of catenary trucks. However, the investment per kilometre also varies with the dimensioning of the infrastructure.
- Second, the willingness to pay among the users depends on the overall cost difference between conventional and catenary trucks. This in turn depends on the price difference of the vehicles, the energy prices and some other factors which are not only influenced by market development but also by the political frame conditions.
- It is quite impossible at the moment to calculate a meaningful payback period at least for the German case. It depends heavily on the intensity of use. Particularly in the early market phase, economic operation is not possible.

Operational challenges around deploying and operating ERS infrastructure

- The ERS demonstration projects in Sweden have shown promising results. They have not had many issues with the infrastructure to-date.
- One of the main challenges with deploying the infrastructure is to make sure during the planning process that there are good access points to the electrical grid. When the testing sites were planned, one of them was parallel to a HV cable, so it was easy to connect to the high voltage (HV) grid; for another site, there was a 10kV cable that wasn't of high enough power, so they needed an additional cable to connect to HV, which introduced a practical / cost challenge.

- Safety issues should be considered, particularly with the pantograph. When there is a system in a large-scale market with pantographs and ownership of truck with pantograph, is there a system in place to ensure operators / drivers regularly check the pantograph? There is a need to avoid a situation where a pantograph is worn out or broken. A system needs to be in place where trucks that are using the systems are monitored (entering / exiting). Realistic solutions already exist.
- There is a need to consider how to solve regulatory issues – e.g. how to measure the electricity to bill operators for using it. This is a problem as it is DC measurement – calibration devices are not yet approved. This is not a technical problem; rather it is a problem for permissions.
  There are some opinions that ERS may interfere with traffic flows.
- The system will primarily be on highways. Infrastructure will only be installed on the outside lane – construction is on the outside of the road. A very short period is required to arrange everything over the outside lane. Some periods will be needed to close the outside lane, but if it's on a highway with more than one lane then it will be less disruptive. Night or weekend work is preferred.
- There was one situation during a trial where the poles were set up in the middle of the highway – the entire highway had to be closed for 10 minutes.

ERS infrastructure build rate limitations

- For the demonstration projects, the time span was two years between starting and finalising the infrastructure; however, this should be considered as an upper limit. The planning procedure is very long in Germany – this can be considered a main barrier to deployment.
- With respect to the maximum number of kilometres that can realistically be constructed, Siemens (the infrastructure provider for the field trials) said not to be shy about this number – there is a not much a limitation on the infrastructure. Some years will be needed in the beginning to develop the team and assemble engineering knowledge, but once this has been achieved there will not be a big limitation on installations.
- The main limitations for the ERS trials can be considered to be: political indecision; setting up business models; and pre-finance of infrastructure with government funding, including construction costs.

Opinions on ownership of ERS infrastructure / how it's funded

***Please note** these are the opinions of some stakeholders based on the trials of ERS infrastructure and should not be treated as conclusive answers.*

- Some negative experiences have been had with PPPs, so it would be more realistic to set up a model where the ownership is with the government – the ownership of roads is also with the government, so this may make sense.
- A model could be set up where the operation is with some private entity – the government will be required to make a starting investment, but there may be some models where the users of the infrastructure may participate in covering the operation costs and the infrastructure construction investment.
- One stakeholder would expect the infrastructure to be publicly owned in Germany, or by a company which is at least partly publicly owned. An alternative would be public tenders with very specific requirements which could also be implemented by private companies. A clear public commitment is necessary in order to give vehicle industry and operators the necessary certainty.

- Another stakeholder specified that the grid could in future be operated by a grid operator (analogous to the existing electricity grid). The grid construction is probably only possible with state support / guarantees, as the investment risk is high.

Main limiting factors to further ERS deployment beyond trials

- One of the main limiting factors can be considered to be political indecision – all knowledge thus far shows that ERS is a good idea, so it needs to be brought on the agenda of large OEMs. Scania is currently very engaged; and Volkswagen is beginning to catch up to Scania. All factors need to be integrated so nothing stops it from continuing deployment.
- For the technology, there is a necessity to reach a point where it is good to make a decision – all of the positives / negatives of a technology cannot be assessed. OEMs don't know where to invest. The right point needs to be reached where the technology strategy is decided, and a technology is focused on, i.e. the point where being technology-agnostic no longer applies.
- Other limiting factors include: uncertainty about the “right” technology for decarbonisation of the HGV fleet; public budget constraints; and time and effort for planning processes.
- Additional limiting factors noted by stakeholders include: provision of suitable vehicles; investment risk for the infrastructure development; restriction of vehicle usage to electrified lanes; lack of standardisation of ERS; and competing drive alternatives preventing planning security (e.g. BEVs, FCEVs, and e-fuels).
- For emerging business models, it was noted that shuttle operation on highly frequented routes could be an interesting proposition, which could also resolve some issues of haulage companies with difficulties finding driving staff for long-haul operation.
- It was noted that financing of infrastructure operation through electricity sales (including infrastructure charge) by an operator could represent a sustainable business model.

A2 Appendix 2 – Breakdown of component weights by different HGV size class

The table below presents a breakdown of the weights of different components within each of the different size classes considered within the modelling – this information was used to calculate the limits on available energy storage for each vehicle type.

Table A1 Breakdown of component weights [kg] by different HGV size class

		Small Rigid Truck (12t GVW)	Large Rigid Truck (26t GVW)	Artic Truck (Curtainsider) (40t GVW)
Powertrain system	Engine system	518	1,123	1,124
	Coolant system	37	81	140
	Fuel system	47	102	80
	Exhaust system	100	217	70
	Transmission system	283	614	558
Electrical system	Electrical system	83	180	265
Chassis system	Chassis frame / mounting system	410	889	3,439
	Suspension system	1,064	2,306	2,328
	Braking system	83	180	784
	Wheels and Tyres	539	1,168	1,352
Cabin /body system	Cabin system	600	1,300	1,153
	Body system	2,000	4,333	2,100
Other	Other	435	935	1,158
Payload	Payload	5,800	12,575	25,450
	Total Kerb Weight	6,200	13,425	14,550

A3 Appendix 3 – Market shares of HGV powertrains used within scenarios

The table below presents the market shares of different HGV powertrains for each scenario considered within the modelling for new vehicle sales.

Table A2 Market shares of different HGV powertrains for each scenario – new vehicle sales

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Scenario 1 - Hydrogen										
D-ICE	31,904	30,559	25,910	22,749	5,529	0	0	0	0	0
D-ERS	0	0	0	0	0	0	0	0	0	0
D-REEV	0	478	3,656	4,247	4,866	1,238	630	0	0	0
BEV	0	0	0	1,213	3,650	5,573	5,984	6,400	6,502	6,606
BEV-ERS	0	0	0	0	0	0	0	0	0	0
FCEV	0	0	0	836	15,045	22,801	23,507	24,205	24,592	24,985
FCEV-ERS	0	0	0	0	0	0	0	0	0	0
FC-REEV	0	0	0	0	0	0	0	0	0	0
Total	**31,904**	**31,038**	**29,567**	**29,045**	**29,090**	**29,613**	**30,121**	**30,605**	**31,094**	**31,591**
% ZEV	***0%***	***0%***	***0%***	***7%***	***64%***	***96%***	***98%***	***100.0%***	***100.0%***	***100.0%***
Scenario 2 - Battery										
D-ICE	31,904	30,171	24,337	17,805	7,222	0	0	0	0	0
D-ERS	0	0	0	0	0	0	0	0	0	0
D-REEV	0	478	3,656	4,247	4,866	1,238	630	0	0	0
BEV	0	388	1,573	6,993	17,002	28,374	29,491	30,605	31,094	31,591
BEV-ERS	0	0	0	0	0	0	0	0	0	0
FCEV	0	0	0	0	0	0	0	0	0	0
FCEV-ERS	0	0	0	0	0	0	0	0	0	0
FC-REEV	0	0	0	0	0	0	0	0	0	0
Total	**31,904**	**31,038**	**29,567**	**29,045**	**29,090**	**29,613**	**30,121**	**30,605**	**31,094**	**31,591**
% ZEV	***0%***	***1%***	***5%***	***24%***	***58%***	***96%***	***98%***	***100.0%***	***100.0%***	***100.0%***
Scenario 3 – Battery ERS										
D-ICE	31,904	30,559	25,910	22,749	5,529	0	0	0	0	0
D-ERS	0	0	0	0	0	0	0	0	0	0
D-REEV	0	478	3,656	4,247	4,866	1,238	630	0	0	0
BEV	0	0	0	1,213	7,300	11,146	11,967	12,800	13,004	13,212
BEV-ERS	0	0	0	836	11,395	17,228	17,524	17,806	18,090	18,379
FCEV	0	0	0	0	0	0	0	0	0	0
FCEV-ERS	0	0	0	0	0	0	0	0	0	0
FC-REEV	0	0	0	0	0	0	0	0	0	0
Total	**31,904**	**31,038**	**29,567**	**29,045**	**29,090**	**29,613**	**30,121**	**30,605**	**31,094**	**31,591**
% ZEV	***0%***	***0%***	***0%***	***7%***	***64%***	***96%***	***98%***	***100.0%***	***100.0%***	***100.0%***
Scenario 4 - H2 ERS										
D-ICE	31,904	30,171	24,337	17,805	7,222	0	0	0	0	0

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
D-ERS	0	0	0	0	0	0	0	0	0	0
D-REEV	0	478	3,656	4,247	4,866	1,238	630	0	0	0
BEV	0	388	1,233	3,640	7,300	11,146	11,967	12,800	13,004	13,212
BEV-ERS	0	0	0	0	0	0	0	0	0	0
FCEV	0	0	0	0	0	0	0	0	0	0
FCEV-ERS	0	0	340	3,352	9,703	17,228	17,524	17,806	18,090	18,379
FC-REEV	0	0	0	0	0	0	0	0	0	0
Total	**31,904**	**31,038**	**29,567**	**29,045**	**29,090**	**29,613**	**30,121**	**30,605**	**31,094**	**31,591**
% ZEV	***0%***	***1%***	***5%***	***24%***	***58%***	***96%***	***98%***	***100.0%***	***100.0%***	***100.0%***
Scenario 5 - Range extended H2										
D-ICE	31,904	30,171	24,337	17,805	7,222	0	0	0	0	0
D-ERS	0	0	0	0	0	0	0	0	0	0
D-REEV	0	478	3,656	4,247	4,866	1,238	630	0	0	0
BEV	0	388	1,233	3,640	7,300	11,146	11,967	12,800	13,004	13,212
BEV-ERS	0	0	0	0	0	0	0	0	0	0
FCEV	0	0	0	0	0	0	0	0	0	0
FCEV-ERS	0	0	0	0	0	0	0	0	0	0
FC-REEV	0	0	340	3,352	9,703	17,228	17,524	17,806	18,090	18,379
Total	**31,904**	**31,038**	**29,567**	**29,045**	**29,090**	**29,613**	**30,121**	**30,605**	**31,094**	**31,591**
% ZEV	***0%***	***1%***	***5%***	***24%***	***58%***	***96%***	***98%***	***100.0%***	***100.0%***	***100.0%***
Scenario 6 - PHEV										
D-ICE	31,904	30,171	24,337	17,805	7,222	0	0	0	0	0
D-ERS	0	0	0	0	0	0	0	0	0	0
D-REEV	0	478	3,996	7,600	14,569	18,467	18,154	17,806	18,090	18,379
BEV	0	388	1,233	3,640	7,300	11,146	11,967	12,800	13,004	13,212
BEV-ERS	0	0	0	0	0	0	0	0	0	0
FCEV	0	0	0	0	0	0	0	0	0	0
FCEV-ERS	0	0	0	0	0	0	0	0	0	0
FC-REEV	0	0	0	0	0	0	0	0	0	0
Total	**31,904**	**31,038**	**29,567**	**29,045**	**29,090**	**29,613**	**30,121**	**30,605**	**31,094**	**31,591**
% ZEV	***0%***	***1%***	***4%***	***13%***	***25%***	***38%***	***40%***	***41.8%***	***41.8%***	***41.8%***

The table below presents the market shares of different HGV powertrains for each scenario considered within the modelling for the total number of vehicles in the parc.

Table A3 Market shares of different HGV powertrains for each scenario – total number of vehicles in parc

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Scenario 1 - Hydrogen										
D-ICE	398,800	386,552	356,847	327,866	244,967	130,945	45,183	11,572	1,007	0
D-ERS	0	0	0	0	0	0	0	0	0	0
D-REEV	0	1,417	12,736	29,125	45,226	44,667	32,613	16,604	6,739	1,610
BEV	0	0	0	1,798	13,352	34,132	55,262	69,895	77,907	81,771
BEV-ERS	0	0	0	0	0	0	0	0	0	0

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
FCEV	0	0	0	4,275	60,085	160,415	243,453	284,495	303,026	311,511
FCEV-ERS	0	0	0	0	0	0	0	0	0	0
FC-REEV	0	0	0	0	0	0	0	0	0	0
Total	**398,800**	**387,969**	**369,583**	**363,065**	**363,630**	**370,159**	**376,511**	**382,566**	**388,680**	**394,891**
% ZEV	***0%***	***0%***	***0%***	***2%***	***20%***	***53%***	***79%***	***92.6%***	***98.0%***	***99.6%***

Scenario 2 - Battery

D-ICE	398,800	385,402	350,644	304,563	224,907	120,023	42,083	10,632	1,529	0
D-ERS	0	0	0	0	0	0	0	0	0	0
D-REEV	0	1,417	12,736	29,125	45,226	44,667	32,613	16,604	6,739	1,610
BEV	0	1,150	6,203	29,376	93,496	205,469	301,815	355,330	380,411	393,281
BEV-ERS	0	0	0	0	0	0	0	0	0	0
FCEV	0	0	0	0	0	0	0	0	0	0
FCEV-ERS	0	0	0	0	0	0	0	0	0	0
FC-REEV	0	0	0	0	0	0	0	0	0	0
Total	**398,800**	**387,969**	**369,583**	**363,065**	**363,630**	**370,159**	**376,511**	**382,566**	**388,680**	**394,891**
% ZEV	***0%***	***0%***	***2%***	***8%***	***26%***	***56%***	***80%***	***92.9%***	***97.9%***	***99.6%***

Scenario 3 - Battery ERS

D-ICE	398,800	386,552	352,185	308,554	220,345	115,733	42,142	11,420	1,599	0
D-ERS	0	0	0	0	0	0	0	0	0	0
D-REEV	0	1,417	12,736	29,125	45,226	44,667	32,613	16,604	6,739	1,610
BEV	0	0	4,661	18,477	45,176	83,538	120,108	146,610	161,413	169,229
BEV-ERS	0	0	2	6,908	52,883	126,221	181,648	207,932	218,930	224,052
FCEV	0	0	0	0	0	0	0	0	0	0
FCEV-ERS	0	0	0	0	0	0	0	0	0	0
FC-REEV	0	0	0	0	0	0	0	0	0	0
Total	**398,800**	**387,969**	**369,585**	**363,065**	**363,630**	**370,159**	**376,511**	**382,566**	**388,680**	**394,891**
% ZEV	***0%***	***0%***	***1%***	***7%***	***27%***	***57%***	***80%***	***92.7%***	***97.9%***	***99.6%***

Scenario 4 - H2 ERS

D-ICE	398,800	385,402	350,644	304,563	224,907	120,023	42,083	10,632	1,529	0
D-ERS	0	0	0	0	0	0	0	0	0	0
D-REEV	0	1,417	12,736	29,125	45,226	44,667	32,613	16,604	6,739	1,610
BEV	0	1,150	5,197	17,100	41,550	78,736	114,730	141,100	155,814	163,541
BEV-ERS	0	0	0	0	0	0	0	0	0	0
FCEV	0	0	0	0	0	0	0	0	0	0
FCEV-ERS	0	1	1,008	12,277	51,947	126,733	187,086	214,230	224,597	229,740
FC-REEV	0	0	0	0	0	0	0	0	0	0
Total	**398,800**	**387,970**	**369,584**	**363,065**	**363,630**	**370,159**	**376,511**	**382,566**	**388,680**	**394,891**
% ZEV	***0%***	***0%***	***2%***	***8%***	***26%***	***56%***	***80%***	***92.9%***	***97.9%***	***99.6%***

Scenario 5 - Range extended H2

D-ICE	398,800	385,402	350,644	304,563	224,907	120,023	42,083	10,632	1,529	0
D-ERS	0	0	0	0	0	0	0	0	0	0
D-REEV	0	1,417	12,736	29,125	45,226	44,667	32,613	16,604	6,739	1,610

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
BEV	0	1,150	5,197	17,100	41,550	78,736	114,730	141,100	155,814	163,541
BEV-ERS	0	0	0	0	0	0	0	0	0	0
FCEV	0	0	0	0	0	0	0	0	0	0
FCEV-ERS	0	0	0	0	0	0	0	0	0	0
FC-REEV	0	0	1,007	12,277	51,947	126,733	187,086	214,230	224,597	229,740
Total	**398,800**	**387,969**	**369,583**	**363,065**	**363,630**	**370,159**	**376,511**	**382,566**	**388,680**	**394,891**
% ZEV	***0%***	***0%***	***2%***	***8%***	***26%***	***56%***	***80%***	***92.9%***	***97.9%***	***99.6%***
Scenario 6 - PHEV										
D-ICE	398,800	385,402	350,644	304,563	224,907	120,023	42,083	10,632	1,529	0
D-ERS	0	0	0	0	0	0	0	0	0	0
D-REEV	0	1,417	13,743	41,402	97,173	171,400	219,698	230,834	231,336	231,350
BEV	0	1,150	5,197	17,100	41,550	78,736	114,730	141,100	155,814	163,541
BEV-ERS	0	0	0	0	0	0	0	0	0	0
FCEV	0	0	0	0	0	0	0	0	0	0
FCEV-ERS	0	0	0	0	0	0	0	0	0	0
FC-REEV	0	0	0	0	0	0	0	0	0	0
Total	**398,800**	**387,969**	**369,583**	**363,065**	**363,630**	**370,159**	**376,511**	**382,566**	**388,680**	**394,891**
% ZEV	***0%***	***0%***	***1%***	***5%***	***11%***	***21%***	***30%***	***36.9%***	***40.1%***	***41.4%***

A4 Appendix 4 – Tabulated results of infrastructure cost and requirement modelling

A4.1 Summary results

Each of the tables below contain the tabulated results for each individual scenario in five-year intervals:

- Vehicle energy consumption,
- Annualised infrastructure cost results,
- total annualised fuel costs by scenario,
- Combined total annualised fuel and infrastructure costs,
- And cumulative in-year CAPEX costs.

Table A4 Vehicle energy consumption by scenario, for all fuels [PJ]

Scenario	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Baseline	357	333	298	269	248	234	226	219	216	216
Hydrogen	357	334	297	265	215	157	118	103	98	97
Battery	357	334	296	256	204	137	90	73	68	67
Bat-ERS	357	334	296	257	195	129	88	72	67	66
H2-ERS	357	334	296	257	206	143	99	82	77	76
H2-REX	357	334	296	257	209	150	109	92	87	86
PHEV	357	334	296	260	224	192	171	160	156	155

Table A5 Total annualised infrastructure cost (societal) [million £]

Scenario	2020	2025	2030	2035	2040	2045	2050	2055	2060
Baseline	£-	£-	£-	£-	£-	£-	£-	£-	£-
Hydrogen	**£ 0.3**	**£ 2.0**	**£ 16.3**	**£ 191.8**	**£ 446.4**	**£ 612.8**	**£ 664.1**	**£ 691.3**	**£ 698.4**
Battery	**£ 0.6**	**£ 6.1**	**£ 42.7**	**£ 169.0**	**£ 400.3**	**£ 574.0**	**£ 628.0**	**£ 603.7**	**£ 553.3**
Bat-ERS	£0.3	£5.7	£39.5	£185.6	£422.5	£605.7	£678.9	£674.4	£659.7
H2-ERS	**£ 0.6**	**£ 8.9**	**£ 54.9**	**£ 194.9**	**£ 430.9**	**£ 619.0**	**£ 708.5**	**£ 734.1**	**£ 734.6**
H2-REX	**£ 0.6**	**£ 7.6**	**£ 58.0**	**£ 224.8**	**£ 513.6**	**£ 715.9**	**£ 773.9**	**£ 774.6**	**£ 742.9**
PHEV	£0.6	£5.0	£28.2	£100.6	£228.4	£324.5	£355.3	£342.6	£316.0

Table A6 Total annualised fuel cost (societal) by scenario, all Infrastructure [million £]

Scenario	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Baseline	£3,308	£3,233	£3,306	£3,456	£3,252	£3,076	£2,961	£2,878	£2,896	£2,954

Scenario	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Hydrogen	£3,311	£3,241	£3,309	£3,446	£3,074	£2,121	£1,596	£1,368	£1,302	£1,291
Battery	£3,311	£3,241	£3,305	£3,406	£2,964	£2,224	£1,483	£937	£870	£858
Bat-ERS	£3,311	£3,241	£3,306	£3,409	£2,916	£2,187	£1,545	£1,068	£995	£980
H2-ERS	£3,311	£3,241	£3,306	£3,420	£2,984	£2,149	£1,583	£1,284	£1,221	£1,209
H2-REX	£3,311	£3,241	£3,307	£3,434	£3,028	£2,187	£1,557	£1,158	£1,089	£1,074
PHEV	£3,311	£3,241	£3,306	£3,424	£3,114	£2,735	£2,360	£2,035	£2,003	£2,021

Table A7 Total annualised fuel and infrastructure cost (societal) by scenario, all infrastructure [million £]

Scenario	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Baseline	£3,308	£3,233	£3,306	£3,456	£3,252	£3,076	£2,961	£2,878	£2,896	£2,954
Hydrogen	£3,311	£3,242	£3,311	£3,463	£3,266	£2,567	£2,209	£2,032	£1,993	£1,990
Battery	£3,311	£3,242	£3,311	£3,449	£3,133	£2,624	£2,057	£1,565	£1,474	£1,412
Bat-ERS	£3,311	£3,242	£3,312	£3,449	£3,102	£2,610	£2,150	£1,747	£1,670	£1,640
H2-ERS	£3,311	£3,242	£3,315	£3,475	£3,178	£2,580	£2,202	£1,992	£1,955	£1,943
H2-REX	£3,311	£3,242	£3,315	£3,492	£3,253	£2,701	£2,273	£1,931	£1,864	£1,817
PHEV	£3,311	£3,242	£3,311	£3,452	£3,214	£2,964	£2,685	£2,390	£2,346	£2,337

Table A8 Cumulative in-year CAPEX costs (societal) [billion £]

Scenario	2020	2025	2030	2035	2040	2045	2050	2055	2060
Baseline	£-	£-	£-	£-	£-	£-	£-	£-	£-
Hydrogen	£-	£0.00	£0.02	£0.18	£2.04	£4.75	£6.53	£7.11	£7.45
Battery	£-	£0.01	£0.07	£0.51	£2.04	£4.85	£7.02	£8.09	£9.25
Bat-ERS	£-	£0.00	£0.07	£0.46	£2.14	£4.85	£6.98	£8.06	£9.02
H2-ERS	£-	£0.01	£0.10	£0.59	£2.08	£4.60	£6.62	£7.63	£8.03
H2-REX	£-	£0.01	£0.09	£0.65	£2.53	£5.79	£8.13	£9.05	£9.89
PHEV	£-	£0.01	£0.06	£0.34	£1.21	£2.77	£3.98	£4.61	£5.29

A4.2 Energy demand for HGVs

The data associated with the energy demand for each scenario is presented in the table below, split out into five-year intervals for each scenario.

Table A9 Vehicle energy consumption (by fuel), all scenarios [PJ]

Fuel	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Scenario 1 - Hydrogen										
Diesel	357	334	297	262	191	95	31	7	1	0
Electricity	0	0	1	2	3	4	5	5	5	5
Hydrogen	0	0	0	1	21	58	83	91	92	92
Total	**357**	**334**	**297**	**265**	**215**	**157**	**118**	**103**	**98**	**97**
Scenario 2 - Battery										
Diesel	357	334	295	251	185	95	31	7	1	0
Electricity	0	0	1	5	18	42	59	65	66	67
Hydrogen	0	0	0	0	0	0	0	0	0	0
Total	**357**	**334**	**296**	**256**	**204**	**137**	**90**	**73**	**68**	**67**
Scenario 3 - Battery ERS										
Diesel	357	334	295	251	173	85	29	8	1	0
Electricity	0	0	1	5	22	44	59	64	65	66
Hydrogen	0	0	0	0	0	0	0	0	0	0
Total	**357**	**334**	**296**	**257**	**195**	**129**	**88**	**72**	**67**	**66**
Scenario 4 - H2 ERS										
Diesel	357	334	295	251	185	95	31	7	1	0
Electricity	0	0	1	4	11	21	29	32	32	32
Hydrogen	0	0	0	2	10	27	39	43	44	44
Total	**357**	**334**	**296**	**257**	**206**	**143**	**99**	**82**	**77**	**76**
Scenario 5 - Range extended H2										
Diesel	357	334	295	251	185	95	31	7	1	0
Electricity	0	0	1	4	11	22	30	34	35	36
Hydrogen	0	0	0	2	12	33	47	51	51	50
Total	**357**	**334**	**296**	**257**	**209**	**150**	**109**	**92**	**87**	**86**
Scenario 6 - PHEV										
Diesel	357	334	295	256	213	171	141	127	121	119
Electricity	0	0	1	4	11	22	30	33	35	35
Hydrogen	0	0	0	0	0	0	0	0	0	0
Total	**357**	**334**	**296**	**260**	**224**	**192**	**171**	**160**	**156**	**155**

A4.3 Zero emission HGV refuelling infrastructure costs

A4.3.1 Annual infrastructure costs

The table below shows the specific values for the annual infrastructure costs, with the costs split between infrastructure types in 5-year intervals.

Table A10 Total annual costs (societal), all scenarios [million £]

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Scenario 1 - Hydrogen										
E-Depot	£-	£0.3	£2.0	£4.8	£9.6	£14.0	£16.2	£16.6	£16	£16
E-UltraRapid	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
ERS	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
H2-Station	£-	£-	£-	£11.5	£182.3	£432.5	£596.6	£647.5	£675	£683
D-Fuel	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
Total	£-	£0.3	£2.0	£16.3	£191.8	£446.4	£612.8	£664.1	£691.3	£698.4
Scenario 2 - Battery										
E-Depot	£-	£0.6	£6.1	£41.3	£158.0	£369.8	£529.6	£580.6	£559	£514
E-UltraRapid	£-	£-	£-	£1.4	£11.0	£30.5	£44.4	£47.4	£45	£39
ERS	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
H2-Station	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
D-Fuel	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
Total	£-	£0.6	£6.1	£42.7	£169.0	£400.3	£574.0	£628.0	£603.7	£553.3
Scenario 3 - Battery ERS										
E-Depot	£-	£0.3	£5.7	£28.9	£120.0	£245.9	£330.6	£358.9	£338	£320
E-UltraRapid	£-	£-	£-	£-	£-	£-	£-	£-	£-	£0
ERS	£-	£-	£-	£10.7	£65.6	£176.6	£275.0	£320.0	£337	£340
H2-Station	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
D-Fuel	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
Total	£-	£0.3	£5.7	£39.5	£185.6	£422.5	£605.7	£678.9	£674.4	£659.7
Scenario 4 - H2 ERS										
E-Depot	£-	£0.6	£3.3	£8.3	£15.8	£23.3	£28.2	£30.2	£30	£30
E-UltraRapid	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
ERS	£-	£-	£3.6	£21.9	£75.2	£166.1	£255.3	£314.3	£328	£332
H2-Station	£-	£-	£2.0	£24.7	£103.9	£241.5	£335.4	£364.0	£376	£372
D-Fuel	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
Total	£-	£0.6	£8.9	£54.9	£194.9	£430.9	£619.0	£708.5	£734.1	£734.6
Scenario 5 - Range extended H2										
E-Depot	£-	£0.6	£5.0	£28.2	£100.6	£228.4	£324.5	£355.3	£343	£316
E-UltraRapid	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
ERS	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
H2-Station	£-	£-	£2.7	£29.8	£124.2	£285.2	£391.5	£418.6	£432	£427
D-Fuel	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Total	£-	£0.6	£7.6	£58.0	£224.8	£513.6	£715.9	£773.9	£774.6	£742.9
Scenario 6 - PHEV										
E-Depot	£-	£0.6	£5.0	£28.2	£100.6	£228.4	£324.5	£355.3	£343	£316
E-UltraRapid	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
ERS	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
H2-Station	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
D-Fuel	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
Total	£-	£0.6	£5.0	£28.2	£100.6	£228.4	£324.5	£355.3	£342.6	£316.0

A4.3.2 In-year CAPEX Costs

The cumulative in-year CAPEX costs presented below, with results split between infrastructure type and in 5-year intervals.

Table A11 Cumulative in-year CAPEX costs (societal), all scenarios [billion £]

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Scenario 1 - Hydrogen										
E-Depot	£-	£0.0	£0.0	£0.1	£0.1	£0.2	£0.2	£0.2	£0.3	£0.3
E-UltraRapid	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
ERS	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
H2-Station	£-	£-	£-	£0.1	£1.9	£4.6	£6.3	£6.9	£7.2	£7.3
D-Fuel	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
Total	£-	£0.0	£0.0	£0.2	£2.0	£4.7	£6.5	£7.1	£7.4	£7.7
Total 5-year		£0.00	£0.02	£0.15	£1.87	£2.70	£1.78	£0.57	£0.34	£0.23
Scenario 2 - Battery										
E-Depot	£-	£0.0	£0.1	£0.5	£1.9	£4.5	£6.5	£7.5	£8.6	£10.5
E-UltraRapid	£-	£-	£-	£0.0	£0.1	£0.4	£0.5	£0.6	£0.7	£0.8
ERS	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
H2-Station	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
D-Fuel	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
Total	£-	£0.0	£0.1	£0.5	£2.0	£4.9	£7.0	£8.1	£9.2	£11.3
Total 5-year		£0.01	£0.07	£0.44	£1.53	£2.81	£2.17	£1.07	£1.16	£2.10
Scenario 3 - Battery ERS										
E-Depot	£ -	£0.0	£0.1	£0.3	£1.4	£3.0	£4.1	£4.7	£5.5	£6.7
E-UltraRapid	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
ERS	£ -	£ -	£ -	£0.1	£0.7	£1.9	£2.9	£3.4	£3.6	£3.7
H2-Station	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
D-Fuel	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
Total	**£ -**	**£0.0**	**£0.1**	**£0.5**	**£2.1**	**£4.8**	**£7.0**	**£8.1**	**£9.0**	**£10.4**

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Total 5-year		**£0.00**	**£0.06**	**£0.39**	**£1.68**	**£2.70**	**£2.13**	**£1.08**	**£0.96**	**£1.39**
Scenario 4 - H2 ERS										
E-Depot	£-	£0.0	£0.0	£0.1	£0.2	£0.3	£0.4	£0.4	£0.5	£0.6
E-UltraRapid	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
ERS	£-	£-	£0.0	£0.2	£0.8	£1.8	£2.7	£3.3	£3.5	£3.7
H2-Station	£-	£-	£0.0	£0.3	£1.1	£2.6	£3.6	£3.9	£4.0	£4.2
D-Fuel	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
Total	£-	£0.0	£0.1	£0.6	£2.1	£4.6	£6.6	£7.6	£8.0	£8.5
Total 5-year		£0.01	£0.09	£0.49	£1.49	£2.52	£2.03	£1.01	£0.40	£0.47
Scenario 5 - Range extended H2										
E-Depot	£-	£0.0	£0.1	£0.3	£1.2	£2.8	£4.0	£4.6	£5.3	£6.5
E-UltraRapid	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
ERS	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
H2-Station	£-	£-	£0.0	£0.3	£1.3	£3.0	£4.1	£4.4	£4.6	£4.8
D-Fuel	£-	£-	£-	£-	£-	£-	£-	£-	£-	£-
Total	£-	£0.0	£0.1	£0.7	£2.5	£5.8	£8.1	£9.1	£9.9	£11.3
Total 5-year		£0.01	£0.08	£0.57	£1.88	£3.26	£2.34	£0.92	£0.84	£1.36
Scenario 6 - PHEV										
E-Depot	£ -	£0.0	£0.1	£0.3	£1.2	£2.8	£4.0	£4.6	£5.3	£6.5
E-UltraRapid	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
ERS	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
H2-Station	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
D-Fuel	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
Total	**£ -**	**£0.0**	**£0.1**	**£0.3**	**£1.2**	**£2.8**	**£4.0**	**£4.6**	**£5.3**	**£6.5**
Total 5-year		**£0.01**	**£0.05**	**£0.28**	**£0.87**	**£1.55**	**£1.21**	**£0.64**	**£0.68**	**£1.18**

A4.3.3 Annual fuel costs (social only)

The annual vehicle energy costs are shown in the table below, dividing into the fuel costs for diesel, electricity and hydrogen for each scenario in 5-year intervals.

Table A12 Vehicle energy cost (social, excl. tax) [million £]

Fuel	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Scenario 1 - Hydrogen										
Diesel	£3,311	£3,239	£3,287	£3,361	£2,499	£1,250	£401	£ 97	£13	£1
Electricity	£ -	£2	£22	£56	£89	£97	£82	£ 53	£51	£50
Hydrogen	£ -	£ -	£ -	£29	£486	£773	£1,114	£1,218	£1,238	£1,240
Total	**£3,311**	**£3,241**	**£3,309**	**£3,446**	**£3,074**	**£2,121**	**£1,596**	**£1,368**	**£1,302**	**£1,291**
Scenario 2 - Battery										
Diesel	£3,311	£3,237	£3,266	£3,219	£2,430	£1,245	£408	£ 98	£18	£1
Electricity	£ -	£4	£39	£187	£534	£979	£1,076	£839	£853	£858
Hydrogen	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
Total	**£3,311**	**£3,241**	**£3,305**	**£3,406**	**£2,964**	**£2,224**	**£1,483**	**£937**	**£870**	**£858**
Scenario 3 - Battery ERS										
Diesel	£3,311	£3,239	£3,270	£3,226	£2,276	£1,113	£379	£ 99	£17	£1
Electricity	£ -	£2	£36	£183	£641	£1,074	£1,166	£968	£978	£980
Hydrogen	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
Total	**£3,311**	**£3,241**	**£3,306**	**£3,409**	**£2,916**	**£2,187**	**£1,545**	**£1,068**	**£995**	**£980**
Scenario 4 - H2 ERS										
Diesel	£3,311	£3,237	£3,266	£3,219	£2,430	£1,245	£408	£ 98	£18	£1
Electricity	£ -	£4	£36	£141	£326	£544	£649	£608	£617	£619
Hydrogen	£ -	£ -	£4	£60	£228	£360	£526	£577	£586	£589
Total	**£3,311**	**£3,241**	**£3,306**	**£3,420**	**£2,984**	**£2,149**	**£1,583**	**£1,284**	**£1,221**	**£1,209**
Scenario 5 - Range extended H2										
Diesel	£3,311	£3,237	£3,266	£3,219	£2,430	£1,245	£408	£ 98	£18	£1
Electricity	£ -	£4	£36	£139	£318	£504	£517	£377	£390	£396
Hydrogen	£ -	£ -	£5	£75	£280	£438	£633	£682	£681	£678
Total	**£3,311**	**£3,241**	**£3,307**	**£3,434**	**£3,028**	**£2,187**	**£1,557**	**£1,158**	**£1,089**	**£1,074**
Scenario 6 - PHEV										
Diesel	£3,311	£3,237	£3,270	£3,286	£2,800	£2,239	£1,851	£1,663	£1,618	£1,629
Electricity	£ -	£4	£36	£138	£313	£496	£510	£372	£385	£392
Hydrogen	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
Total	**£3,311**	**£3,241**	**£3,306**	**£3,424**	**£3,114**	**£2,735**	**£2,360**	**£2,035**	**£2,003**	**£2,021**

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