THE CENTRE FOR SUSTAINABLE ROAD FREIGHT

White Paper

Decarbonising the UK's Long-Haul Road Freight at Minimum Economic Cost

Technical Report CUED/C-SRF/TR17

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Executive Summary

In July 2019, the UK Government revised its Climate Change Act (2008) to mandate net-zero greenhouse gas (GHG) emissions by 2050. This is an ambitious, but essential objective requiring sweeping changes across the whole of the UK's energy system. It means that the UK needs a full-range of robust and cost-effective, zero-GHG energy system technologies, covering electricity generation, heat, industry, transport and agriculture: implemented from the early 2020's onward.

Land-based freight is an essential service sector, vital to the prosperity of the UK; however, it is also a significant source of GHG and noxious emissions. Within domestic freight, Heavy Goods Vehicles (HGVs) carry 90% of the UK's goods lifted (DfT, 2018a). A zero-emissions alternative to the traditional diesel-powered HGV is vital if the UK is to achieve its net-zero carbon ambition.

The UK's economy has been hit by an unprecedented economic downturn due to the COVID-19 crisis. As the Government assesses the damage and considers policies that can stimulate investment and jobs, this White Paper presents an opportunity to align these two goals: electrifying our major roads to quickly and cost-effectively decarbonise HGVs.

An 'Electric Road System' (ERS) is the primary candidate to deliver the energy needed by the UK's long-distance HGV fleet. ERS deploys roadside infrastructure that allows the most efficient direct use of zero-carbon electricity and hence the lowest societal cost. This approach is scalable and quick to deploy, using known and available technologies, existing delivery bodies such as National Grid, Highways England and the UK's construction industry and infrastructure supply chains: creating significant employment. Truck manufacturers including Scania have indicated they can deliver the modified vehicles and have delivered numerous prototypes for demonstration trials around Europe.

This White Paper sets out the case for a nationwide rollout of ERS through the 2030s. A total investment in the region of £19.3 billion would be required to electrify almost all the UK's *long-haul* freight vehicles, corresponding to 65% of road freight movements. The estimated CO_2 saving would be 13.4 $MtCO_2e$ per annum, along with substantial air quality benefits. The remaining 35% of freight movements are mainly urban deliveries that are expected to move to battery electric lorries over the next 10 years. The investment compares well with the size of other planned infrastructure projects. Work could get underway immediately with an £80 million pilot project in the North East of England.

What is an Electric Road System?

There are several forms of ERS including conductive and inductive systems. The most mature and cost-effective technology is the overhead catenary system, which is the focus of this paper. Figure i shows an overhead catenary installed on a German motorway. There are four such demonstrations underway on public roads across Germany and Sweden that have demonstrated the feasibility of the approach, with a further demonstration being planned in Italy.

The overhead catenary system is a mature and safe technology (commonplace in the railway sector) that consists of a supporting structure built outside the road boundary that holds two catenary cable systems. These wires supply the positive and negative electrical circuit that is picked up through a pantograph collector on the roof of the HGV. The pantograph can be rapidly connected and disconnected automatically as needed. The HGV is free to leave the wires to overtake or complete its journey away from the catenary using a separate on-board battery (approximately the size of an electric car battery), providing zero tailpipe emissions at all times. Any existing or future propulsion technology is compatible with the overhead catenary approach. Indeed, during the transition period it is anticipated that hybrid vehicles will combine catenary power with diesel, bio-gas or hydrogen fuel cells to ensure the necessary operational flexibility.

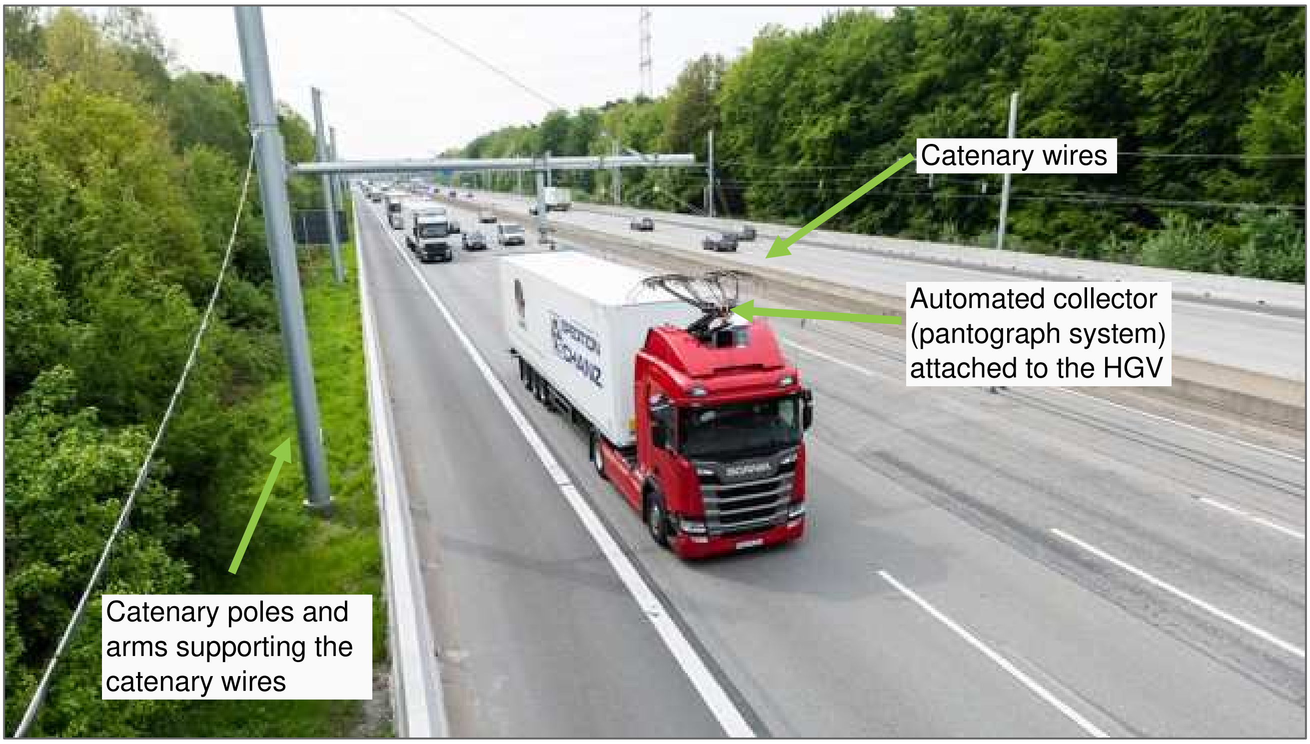


Figure i: Photograph of a Scania HGV operating on a catenary lorry 'eHighway' demonstrator in Germany, from Siemens (2020).

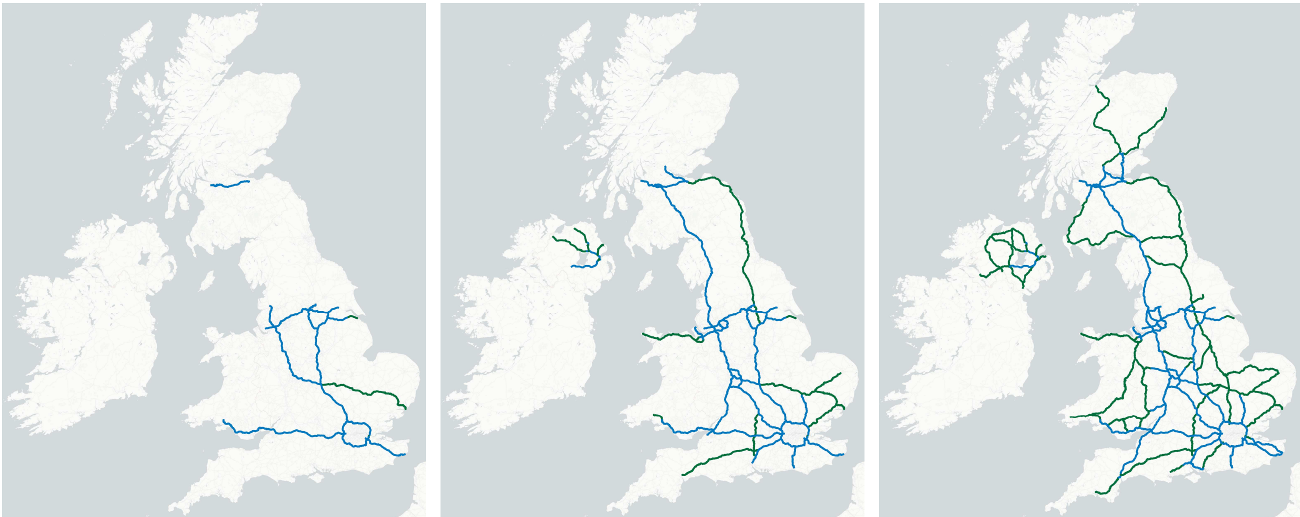
How could zero-emission electric HGVs become a reality in the UK?

The 'UK Electric Motorway System' (UKEMS) project will build the necessary infrastructure across the UK's road network. It is proposed that this is achieved through a four-phase programme. Starting with an £80 million pilot project, leveraging the lessons learnt in Sweden, Germany and Italy, to look at the policy, taxation, and implementation issues specific to the UK. The proposed 40 lane-km South Yorkshire pilot needs to be completed by 2025, so that the main three-phase rollout of the infrastructure can begin. Each of the construction phases of the rollout would take 2-3 years plus associated time for planning, design, procurement, etc. Example rollout phases with estimated costs are shown in Figure ii. The total cost of the final network is estimated to be **£19.3 billion** and covers approximately 65% of all the HGV-kms in the UK. By using battery electric power to travel to and from the network and for urban operations, a very high level of decarbonisation of the road freight sector would be achieved as the carbon intensity of the electricity grid reduces.

Roll-out of the roadside infrastructure could be made even more cost-effective by combining it with other road infrastructure projects such as the intelligent transport systems needed to support connected and autonomous vehicles as well as the 5G network: thus, sharing costs and providing the UK with world-class digital transport and communications infrastructure. With upfront planning, part of the backbone electrical infrastructure could also be shared with cars and vans, through charging points located at motorway services. Much of the cost of high-power motorway-based charging infrastructure for cars is spent getting sufficient electrical power to the roadside, often directly from the National Grid (or devolved equivalent). By sharing this cost between cars and HGVs, the investment risk will be lowered and construction-related disruption reduced.

How would the system pay for itself and generate revenue for HM Treasury?

This paper shows that profitable business models are possible for the vehicle operators and infrastructure providers and that energy sales can generate substantial revenue for HM Treasury. This is a result of the inherent energy efficiency and low economic costs of operating electric lorries. The investment in pantograph-electric vehicles by fleet operators could pay back within 18 months (due to lower energy costs), with substantial headroom to raise revenue through increased electricity excise tax for the government. Investment in electrification infrastructure: catenary cables, substations, etc., could pay back in 15 years, using the profit margin on electricity sales to vehicles. The system would be entirely self-sustaining and could be built and operated using private finance.



Phase 1
Distance [lane-km]: 3,261 km
Construction time: 2.0 years
Infrastructure cost: £5.6 Bn
HGV-km coverage: 31%

Phase 2
Distance [lane-km]: 4,247 km
Construction time: 2.6 years
Infrastructure cost: £5.1 Bn
HGV-km coverage: 50%

Phase 3
Distance [lane-km]: 6,300 km
Construction time: 2.5 years
Infrastructure cost: £7.1 Bn
HGV-km coverage: 65%

Figure ii: Illustrated example of the 3-phase rollout (motorways are blue, A-roads are green).

Summary

Overhead catenaries and compatible HGV’s are the most energy-efficient and cost-effective solution to fully decarbonise the UK’s road freight network. Their deployment is essential if the UK is to achieve its Carbon budgets through to net-zero GHG emissions by 2050. The technology is proven and the transition from the current diesel-centric approach to catenary-powered electric vehicles can be handled with hybrid vehicles. The infrastructure investment can also be partly shared with other investments such as motorway service station charging of cars, the 5G network and the intelligent transport system infrastructure needed to support connected and autonomous vehicles of the future.

The investments in pantograph electric vehicles would pay-back the vehicle operators in 18 months (through lower energy costs) and the electrification infrastructure could pay-back its investors in 15 years (through electricity sales). This makes the infrastructure investment a unique opportunity for private finance. The improved energy efficiency of the freight system will also create sufficient headroom in the economics for substantial government revenues through an electricity excise tax, road user charge or some other form of tax.

This paper shows that under some reasonable pricing scenarios, the revenues could be sufficient to entirely replace the current fuel tax levied on HGVs. In addition, reduced dependence on energy imports would strengthen the UK economy and national energy security.

A three-phase implementation plan is presented with an estimated total cost of **£19.3 billion,** completing in the late 2030s. A preliminary phase is proposed, consisting of an £80 million UK-specific pilot project to prove the efficacy of the approach and remove all uncertainties. This paper seeks support for the catenary approach and the launching of the pilot project.

The Centre for Sustainable Road Freight

The Centre for Sustainable Road Freight (SRF) was founded in 2012 to help industry and Government minimise Carbon emissions from the road freight sector. The SRF brings together three of the UK's leading academic groups: the Cambridge University Engineering Department, the Logistics Research Centre of Heriot Watt University and the Freight and Logistics Research Group at the University of Westminster, along with industry and government partners; to make road freight environmentally, economically and socially sustainable.

The overall aims of the SRF are to:

- perform a comprehensive programme of research on the opportunities for improving the environmental sustainability of road freight transport;
- develop innovative technical and operational solutions to road freight transport challenges;
- assess solutions to meet Government emissions reduction targets for the road freight sector;
- bring together organisations from across the road freight industry in a cooperative group: to develop innovative solutions to reduce fuel consumption and test them in practice.

The SRF receives funding from various UK Government and European sources, particularly UKRI (EPSRC), ETI, and InnovateUK, as well as from industry members.

About this White Paper

This White Paper is the result of extensive SRF research into HGV decarbonisation technologies and logistics as well as consultation with industry and government stakeholders in the road freight sector (see http://www.csrf.ac.uk/research).

Reviewers

Prof Phil Greening (Heriot Watt), Prof John Miles (Arup), Dr Michael Colechin (Cultivate Innovation), Andrew Green (Connected Places Catapult).

List of Abbreviations

CAV – Connected and autonomous vehicles
CCC – Committee on Climate Change
eHGV – Electric heavy goods vehicle
ERS – Electric road system
GHG – Greenhouse gas
GVW – Gross vehicle weight
HGV – Heavy goods vehicle
PP – Payback period
SRN – Strategic road network
TRL – Technology readiness level (See Appendix A for definition)
UKEMS – UK electric motorways system
WTW – Well-to-wheel

Contents

1. Introduction

The UK is a progressive nation in the fight to reduce global warming and the resulting changes in climate. In 2008, the UK introduced pioneering legislation to reduce its emissions of Greenhouse Gases (GHGs). The Climate Change Act (2008) mandated that the nation's GHG emissions must reduce by 80% versus 1990 levels by 2050. The act also contains the provision for a series of GHG 'budgets' that manage the transition between enacting the legislation and the 2050 deadline. In July 2019, the UK Government increased the stringency of the Climate Change Act to deliver 'net-zero' emissions by 2050. Net-zero is a considerable challenge, requiring substantial changes to all aspects of the UK's energy system. However, this challenge also represents an opportunity for the UK, where it can provide both moral and technical leadership in delivering the required transition.

One sector that requires wholesale changes is surface transport. The importance of the transport sector has become acute over recent years with the surface transport sector becoming the highest GHG emitting sector within the UK's energy system (Figure 1). This is due to the increase in transport demand offsetting any system efficiency gains as well as decarbonisation of other sectors, particularly power generation. Surface transport accounted for 25% of UK emissions in 2018 (BEIS 2020).

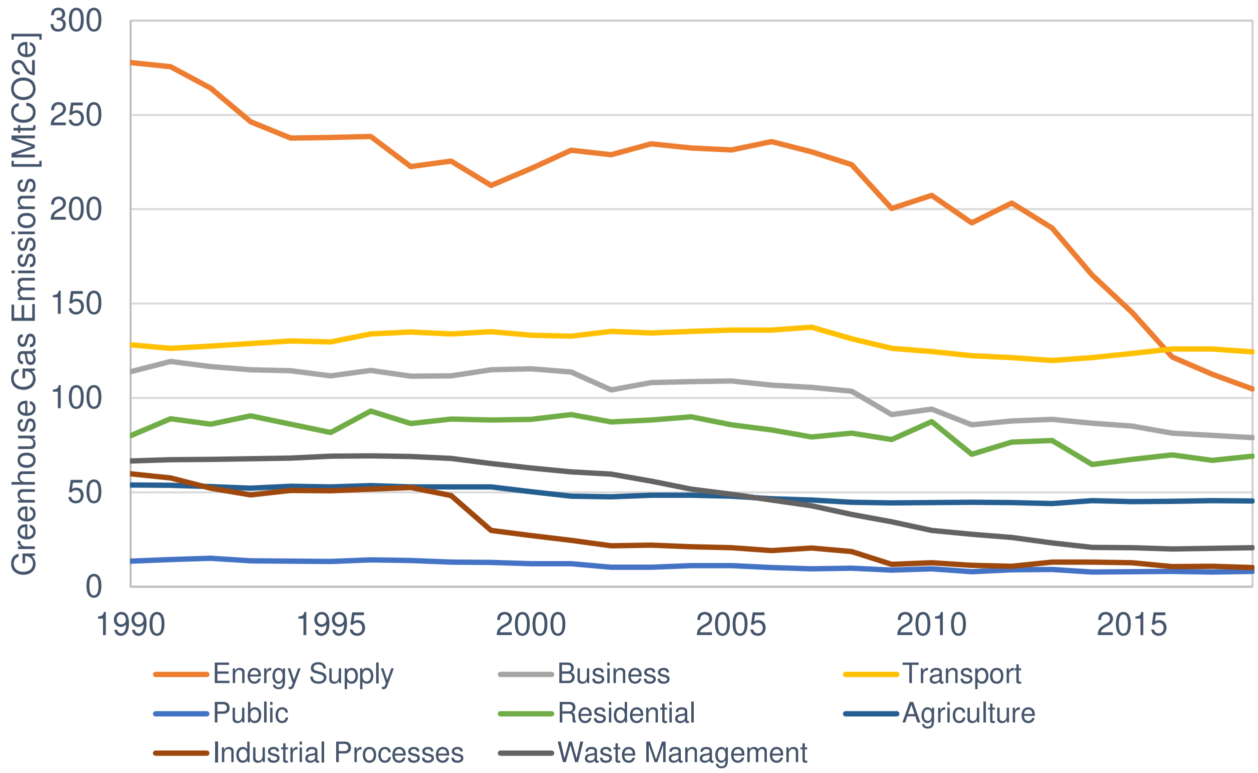


Figure 1: Annual UK greenhouse gas emissions by sector from 1990-2017, data from BEIS (2020).

In recent years, the decarbonisation approach of the car and van industry has become evident. There is now a clear trend towards battery electric vehicles with plug-in hybrids bridging the transition from petrol/diesel power. The battery approach, when coupled with a decarbonised electricity grid, can achieve virtually zero GHG emissions and is compatible with a net-zero future. Efficient battery technology is ideally suited to light-duty passenger vehicles due to the short distances travelled on the majority of journeys. This battery-based approach is also applicable to the smaller Heavy Goods

Vehicles (HGVs) that perform localised freight distribution tasks. Indeed, the electrification of urban logistics is currently underway, with their deployment buoyed by the local air quality benefits.

However, scaling battery technology to the larger long-distance HGVs has several challenges. These challenges are due to the substantial quantities of both energy and power needed for the commercial operation of long-distance HGVs. Finding a deployable solution for all long-distance HGVs is vital for achieving net-zero as they currently represent about 5% of UK's total GHG emissions (BEIS 2020).

There are several possible pathways to decarbonise HGVs. In the short-term, it is necessary to deploy measures that improve energy efficiency. These include reducing weight, improved aerodynamics, use of low-rolling-resistance tyres, improved driver performance, increasing vehicle capacity and a range of measures that can reduce vehicle-km through improved logistics practice.

Research by the Centre for Sustainable Road Freight has shown that it is ***not*** possible to reduce Carbon emissions from the road freight sector by more than 60% without electrification of long-haul vehicles. (Keyes et al. 2018). The same research indicates that it is possible to reduce emissions by 80-90% by 2050 if all long-haul vehicles are electrified.

Electrification of road freight has a key dependence on decarbonisation of the national energy supply. As the 'Carbon factor' of the electricity grid (gCO_2/kWh) decreases, due to increased generation of renewable electricity, any electric vehicle (or vehicle whose fuel is made from electricity) generates lower 'Well-to-Wheel'[1] (WTW) Carbon emissions. However, the dependency is two-way; the more energy that the road freight sector draws from the electricity grid, the more sustainable electricity has to be generated in the country and the more difficult and expensive it is to decarbonise the electricity grid. Consequently, there is a strong need to minimise the amount of energy used by the road freight sector in addition to reducing the Carbon emissions. Reducing energy consumption has the additional benefits of reducing economic costs and consequently improving economic efficiency. It also reduces energy imports and therefore improves the balance of trade and energy security.

The same argument applies to use of natural gas. Even if 'zero-Carbon' routes are used with natural gas (e.g. manufacture of 'Blue Hydrogen' using the Steam Reforming process with Carbon sequestration), it is imperative to minimise energy consumption to reduce gas imports and improve energy security (more than 50% of the UK's natural gas was imported in 2019, mostly from Russia and Qatar).

One further factor that must be considered is the rate at which the decarbonisation technologies can be deployed. Figure 2 shows the rate at which CO_2 must be mitigated to prevent the global temperature rise exceeding 1.5°C. It shows that starting in 2020, CO_2emissions must be essentially zero by 2040. It also shows that maintaining current emission levels for a further 8 years will use up the remaining Carbon budget and the only pathway to maintaining 1.5°C would be to extract very large quantities of CO_2 from the atmosphere.

[1] Well-to-wheel analysis assesses the lifecycle emissions associated with the fuel from production, processing, delivery/transmission, and end-use (used in the vehicle).

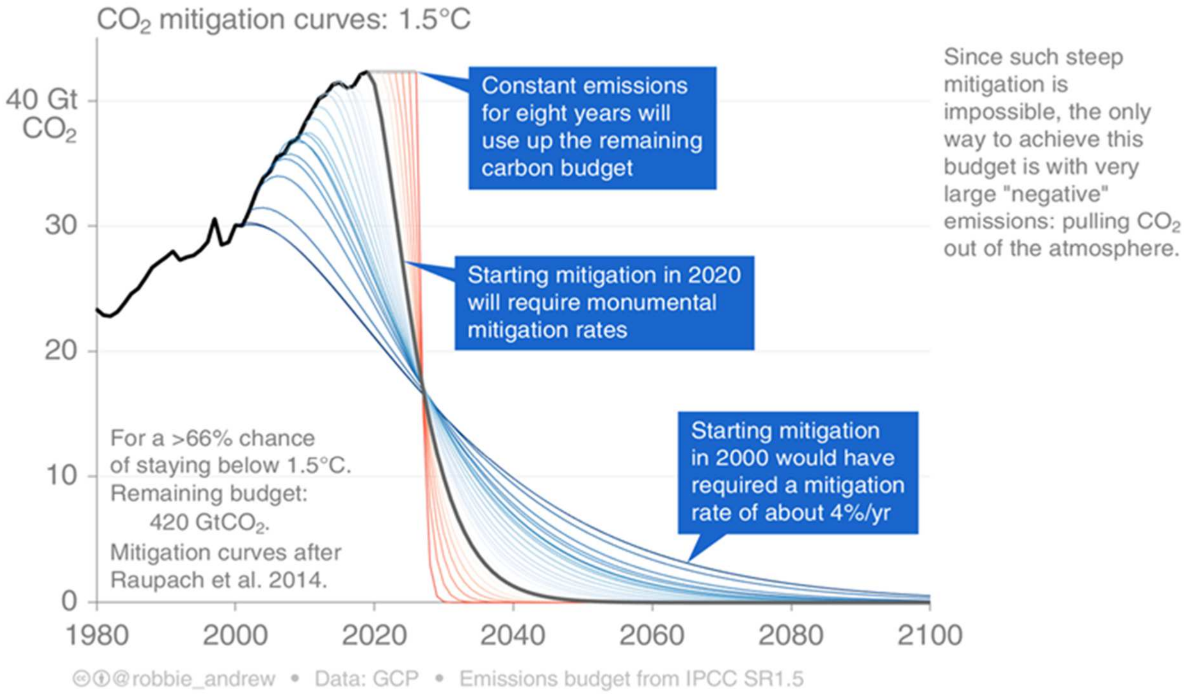


Figure 2: Decarbonisation trajectories needed to maintain global temperature rise to less than 1.5°C, from Andrew (2020).

This highlights the pressing need to use decarbonisation technologies that can be implemented rapidly (i.e. are ‘shovel ready’). The world simply cannot afford to wait 10 or more years for technology to be developed and scaled-up. It is necessary to act much more quickly than that. Consequently, this White Paper discusses options for decarbonising road freight as quickly and economically as possible, whilst also minimising energy consumption.

2. Comparison of Energy Systems

Electrification of urban delivery vehicles using electricity stored in modestly-sized batteries (generally less than 100 kWh) is rapidly increasing, starting with vans and home delivery vehicles, but also including a variety of larger vehicles such as buses, larger delivery lorries up to 26 tonnes, and refuse collection vehicles. Battery power works well for these operations because:

1. the required ranges are relatively low, typically less than 100 km round trip, which keeps battery size, mass and cost acceptable;
2. the vehicles have no gaseous tailpipe emissions, making them environmentally attractive for city use;
3. the vehicles frequently start and stop – so regenerative braking can be applied to 'reuse' electricity: significantly improving energy efficiency;
4. With today's CO_2 intensity of the electricity grid, WTW CO_2 emissions are significantly less for battery electric vehicles than for diesel vehicles. This will improve with time as the electricity grid decarbonises further through increasing renewable electricity generation;
5. Electricity costs are much lower than diesel for equivalent power at the wheels, so that financial payback can be achieved by operators of electric vehicles in a reasonable time.

It is anticipated that battery-electric urban delivery vehicles will become widespread in the UK over the next 10 years, particularly due to the pressure of air quality regulations in cities.

Urban and regional delivery accounts for approximately one third of road freight tonne-km in England. The other two thirds occur on the Strategic Road Network (SRN). (Similar statistics apply for Scotland, Wales and Northern Ireland and for most places in Europe.) So decarbonising long-haul freight is a key priority.

Key issues in choice of technology for long-haul freight vehicles are:

1. Capital and operating costs of vehicles and infrastructure.
2. Operating costs, which are dominated by system efficiency and energy consumption.
3. WTW GHG emissions.
4. Infrastructure requirements.
5. Mass and volume of on-board energy systems.
6. Environmental impacts including air quality, consumption of natural resources, the need for critical and conflict materials (Platinum, Cobalt, etc.), and land use changes.
7. The need for energy imports and their effects on energy security and the balance of trade.
8. Technology Readiness Level (TRL) – for scaling the technology quickly to widespread use.
9. Earliest deployment date.

Table 1 presents a summary of the four main technology choices for long-haul road freight, highlighting these issues. A large amount of literature exists on these technologies and this will not be reviewed in this paper.

Table 1: Summary of features of various vehicle propulsion technologies for long-haul road freight.

Technology	Advantages	Disadvantages
Large-Battery Electric Vehicles	• Low CO_2 emissions on a WTW basis • Zero gaseous tailpipe emissions • **Likely to become the dominant vehicle type for urban delivery and refuse collection in next 10 years.** • High TRL. • Earliest widespread deployment for urban operations: 2025-2030.	• Large batteries increase cost and weight and reduce payload capacity. • High demand for critical/conflict materials • Expensive charging infrastructure required in depots and charging stations. • Long recharging times. • Inadequate range for practical battery sizes – unsuitable for long-haul.
Electric Road System	• Lowest possible energy consumption and WTW CO_2 emissions. • Very low energy cost. • Small batteries only needed for movements between ERS and depots • Zero gaseous tailpipe emissions. • **High TRL: ready to scale.** • Earliest 'wide deployment': 2035-2040†. • Technology neutral, enabling final decisions for net-zero to be deferred. • Infrastructure is complementary to 5G and Connected and Autonomous Vehicle sensing and communications.	• Significant capital investment for charging infrastructure. • Less flexible than other solutions. • 'Unsightly' infrastructure (subjective).
Hydrogen Fuel Cell Vehicles	• Refuelling time and range similar to diesel/gas. • Zero tailpipe emissions. • Low CO_2 emissions if used with 'Green*' or 'Blue**' Hydrogen.	• Very high energy consumption due to low efficiency: very high fuel costs. • Significant capital investment for fuel manufacture and refuelling infrastructure. • Green Hydrogen production is inefficient, expensive and limited scale • Blue Hydrogen production requires large increase in natural gas imports and CO_2 sequestration infrastructure. • Low technology readiness level (TRL). • **Earliest wide deployment: 2040-2050.**
Biofuels	• Can be implemented now and provide GHG emission reductions. • Close to 'drop-in' replacement. • Costs are competitive with diesel.	• Insufficient fuel for widespread adoption: niche solution won't significantly improve national or global CO_2 emissions. • Gaseous tailpipe emissions. • **Wide deployment not possible due to limited availability of biofuels.**
Synthetic Fuels	• Drop-in replacement for diesel. • Use existing refuelling infrastructure. • Low CO_2 emissions if manufactured with sustainable electricity.	• Very high energy cost for fuel manufacture (higher than hydrogen): very high fuel costs. • Requires significant capital investment for fuel manufacture. • Gaseous tailpipe emissions. • Low TRL. • **Earliest wide deployment: 2040-2050.**

* Green Hydrogen is made by electrolysis of water using renewable electricity.
** Blue Hydrogen is made from natural gas using steam reformation, sequestering the resulting CO_2 underground.
† 'Wide deployment' means implementation for essentially all UK registered HGVs.

The main conclusions from the table for long-haul freight vehicles are:

1. Use of battery electric vehicles for long-haul is not practical due to very large batteries required (typically 5-10 times the size of the *largest* batteries used in electric cars and 10-20 times the *average* car battery). The increased vehicle weight dramatically reduces payload capacity. This and the high battery costs make the operation unviable.
2. Biofuels (liquid and gas) can significantly reduce CO_2 emissions, but there is an insufficient supply of biofuel for widespread adoption. This means that although these technologies are useful for decarbonising individual vehicles or fleets, they cannot contribute to substantial CO_2 mitigation at a national or global level and therefore, are not viable as a large-scale solution for surface transport (CCC 2019).
3. Hydrogen-powered vehicles generate zero tailpipe emissions, but manufacture of the hydrogen fuel requires excessive amounts of renewable electricity for the 'Green Hydrogen' route, or substantial increases in imports of natural gas and creation of Carbon sequestration infrastructure, for the 'Blue Hydrogen' route. Both of these routes would be costly, increasing transport costs and reducing the UK's competitiveness (Hacker 2020); both routes are currently at low TRLs for scale-out, so it will be 2040+ before they can be adopted widely.
4. Low-Carbon Synthetic Fuels are generally made using Hydrogen for a feedstock with Carbon captured from CO_2 in the air. Their readiness is dependent on largescale manufacture of blue or green hydrogen and so are a very long-term solution.
5. The most practical solution for long-haul road freight in the UK and Europe is the Electric Road System (ERS). It is the lowest Carbon and lowest energy route for road vehicles. Such systems have been demonstrated in 4 different installations in Europe in recent years and are ready to be scaled-out. Although significant infrastructure is needed, the costs are modest and budgets are within the range of normal highway infrastructure projects. The ERS solution is the most efficient use of zero-Carbon electricity and hence the lowest societal cost, by a large margin. It is the most effective use of the available battery supply and uses known and available (i.e. 'shovel ready') technologies.

The remainder of this White Paper is concerned with the cost-effective deployment of ERS at scale in the UK as a route to almost complete decarbonisation of heavy goods vehicles within the 2030s. Further detail is provided on the ERS approach, its economic benefits, and how it could be deployed across the UK's strategic road network for the benefit of freight operators, logistics companies, low-Carbon energy suppliers and the UK as a whole.

3. The UK Electric Motorways System

This section outlines the proposed 'UK Electric Motorways System' (UKEMS) to achieve rapid wide-spread electrification of road freight, including the required infrastructure and vehicle technologies.

3.1 Electric Road System Infrastructure

Several ERS solutions are available or under development that can be installed on roads to provide on-demand power to charge vehicles in motion. The three technologies can be categorised as:

(i) conductive transmission using overhead lines;
(ii) conductive transmission using a rail or conductor in the road surface;
(iii) inductive (wireless) transmission using electromagnetic pads mounted in the road surface.

The technologies each take a different approach to providing power to the vehicle during motion, and the advantages and disadvantages of the technologies are summarised in Table 1.

Table 2: Summary of the various electric road system (ERS) technologies.

Technology	Advantages	Disadvantages
Overhead Conductive Transmission	• Mature technology adopted from railways. • International technical standards exist. • High technology readiness. • Road surface unaffected by construction. • Efficient transmission of electricity that enables lorries to be propelled and charged simultaneously. • High level of vehicle manoeuvrability • Can largely be installed from hard shoulder without road closure.	• Not usable by passenger and light commercial vehicles. • Visual impact to motorway. • Friction between systems may cause particle generation and wear. • Regular maintenance of infrastructure.
In-Road Conductive Transmission	• Usable by all vehicles. • Efficient transmission of electricity that enables lorries to be propelled and charged simultaneously. • Low visual impact.	• Requires road surface modification. • Low technology readiness. • Rail poses safety risk for road users and may reduce road lifespan. • Friction between systems may cause particle generation and wear • Failure due to ingress of mud, snow, ice, etc. • Restricted vehicle manoeuvrability.
Inductive (Wireless) Transmission	• Usable by all vehicles. • Low visual impact. • No friction between components. • High level of vehicle manoeuvrability.	• Requires significant development. • Low technology readiness. • Low energy efficiency and power (inductive loss). • Providing sufficient power for trucks requires inductive pads at 1-2m spacings (Nicolaides et al. 2017). • Requires road surface to be excavated and replaced: installation disruption. • Risk of road surface failure and increased maintenance due to embedded pads. • Electromagnetic radiation may pose health risks to vehicle occupants. • Most expensive solution.

The only ERS technology that has high technology readiness and that best meets the criteria outlined in Section 2 is overhead conductive transmission. One such system is manufactured by Siemens under the name 'eHighway'. The eHighway's energy supply system uses safe and mature practices from electrified railroads; the two-pole catenary system ensures reliable and stable energy supply to the vehicle at highway speeds. The supply of energy to the overhead contact lines is performed using substations with medium voltage switchgear, power transformers, rectifiers, and controlled inverters and are also able to receive electrical energy generated by the vehicles' regenerative braking system.

The Siemens eHighway is the most feasible ERS infrastructure solution for a variety of reasons:

(i) Many standards for aspects of overhead catenaries exist for electrified railways and can be easily adopted for such an ERS.
(ii) The system has a high TRL of 8, with demonstrator trials in USA, Germany and Sweden.
(iii) The technology is suitable for both rigid and articulated HGVs and can also be utilised by buses and inter-regional coaches.
(iv) The system yields significantly higher energy efficiency than other solutions. During most operations, electricity passes directly from the overhead line, through an inverter to the electric motor on the vehicle. This avoids energy losses passing in and out of a battery and consequently is the most efficient way possible to power an electric vehicle.
(v) The road surface is not compromised with embedded hardware. This is thought to be safer and much lower maintenance than systems which have rails or charging pads embedded in the road surface[2].
(vi) The system has a strong safety record with no high-level risks identified (Bateman et al. 2018) and the concept has been well-established and proven in tram and rail applications.
(vii) Access for road construction and maintenance (including pavement surface management) is easier for overhead catenaries than the other solutions.
(viii) The eHighway system has been developed to handle bridges, interchanges, tunnels, and areas with low clearances to provide continuous charging on motorways (Grünjes 2013).
(ix) Passenger and light duty vehicles generally have acceptable ranges on battery power and can be sufficiently charged at home/depot/motorway services. This is likely to be more convenient and cost-effective than adapting cars for charge-in-motion (Bateman et al. 2018).

3.2 Vehicles

The required vehicle technology on the UKEMS must be cost competitive, maximise energy efficiency, reduce material and energy requirements for vehicle production, be resilient to network outages, significantly reduce Carbon emissions and be able to run on or off ERS roads during the system build-out phases. The most suitable vehicle to meet the criteria has a modular hybrid architecture, illustrated in Figure 3: Illustrative overview of the hybrid vehicle architecture with charge-in-motion capability via the overhead catenary, reproduced from Siemens (2020). These vehicles have an electric powertrain with a motor/generator, a small on-board battery, a pantograph system for charge-in-motion, and a 'range extender' (small combustion engine + generator) to charge the battery pack as needed when the vehicle is off the ERS. These vehicles can also recover energy during braking (i.e. so-called 'regenerative braking') and feed it back into the on-board batteries or, in special cases where beneficial, back into the electricity grid through the catenary system. The UK is currently growing a significant

[2] No significant data on road surface conditions regarding in-built inductive loops or rails (Bateman et al. 2018). Some initial trials have observed cracking in the pavement where installations have been made. This highlights a major concern for road user safety, the effects of embedded hardware on lane changes, and impacts on breakdowns (e.g. HGV tyre blowouts).

industry producing electric lorries, with a number of very successful start-ups. Electrification of lorries provides a prospect for significant revival of the domestic automotive industry.

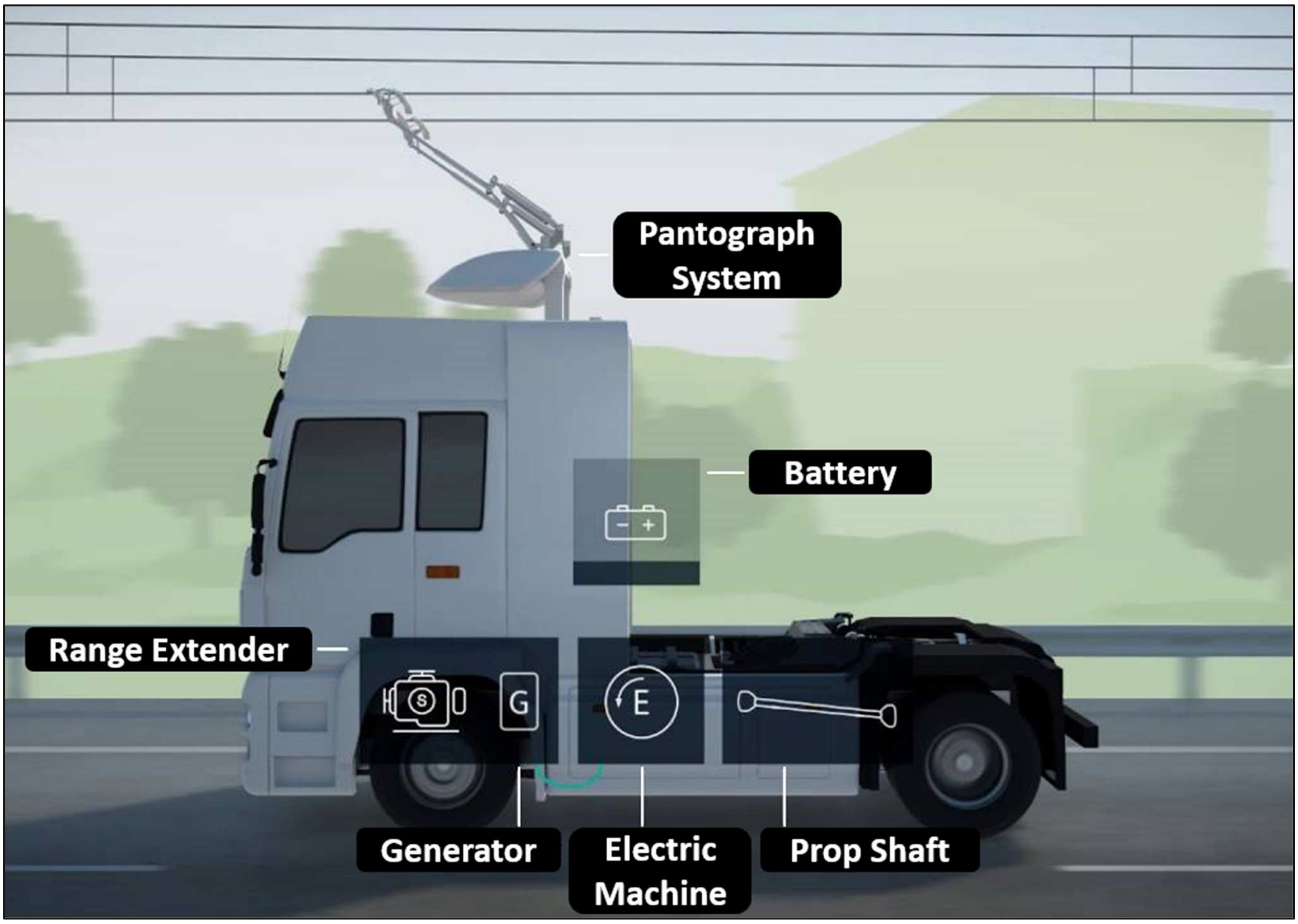


Figure 3: Illustrative overview of the hybrid vehicle architecture with charge-in-motion capability via the overhead catenary, reproduced from Siemens (2020).

3.2.1 Pantograph System

The active pantograph system, mounted on top of the tractor cabin, enables vehicles to seamlessly transition from using the on-board battery to the overhead catenary system when on the UKEMS network. In the current demonstrator trials, the pantograph is manually extended and retracted through the push of an in-cabin button. Functionality has been developed for the pantograph to detect the presence of overhead wires using on-board sensors and automatically connect to the overhead wires, or it can utilise existing lane-keeping features to ensure the pantograph remains connected. The pantograph system can be raised and lowered at any speed up to 100 km/h.

3.2.2 Range Extender

The optional range extender is used to charge the on-board batteries when needed (e.g. the vehicle is off the UKEMS network for an extended period. This will be essential during the transition stages when there is no network coverage in some parts of the country. It will also provide resilience: vehicles will still be able to move freely if part of the network is down.

The UKEMS vehicles are compatible with any type of range extender technology, for example: an Internal Combustion Engine (ICE) using gas, diesel or biofuels, additional battery packs (for volume limited freight applications), or hydrogen fuel cell technology. The range extender can also be scaled (e.g. large, medium, small ICEs) to suit the different vehicle requirements for fleet operators. Importantly, the UKEMS is technology-agnostic for the range extender, deferring the decision for removing the final few percent of CO_2 emissions.

3.2.3 Modular Hybrid Vehicles and the Transition

The hybrid architecture is well-suited to manage the transition during the nationwide rollout of the UKEMS and beyond. The modular nature enables different range extender technologies to be used to augment the electric powertrain. During the early phases of the rollout, the first generation of electric-HGVs (eHGVs) would mostly have larger range extenders (likely gas or diesel-powered ICEs). These would provide mobility in parts of the country not yet served by the UKEMS network and would incrementally change with improving battery energy densities and wider coverage of the UKEMS as construction occurs across the country. When the UKEMS is completely rolled out by 2040, eHGVs with small on-board batteries and pantograph systems would only be required for most operators. There may be some edge cases where a very small proportion of eHGVs require a range extender, for example if they have to travel to remote areas well outside the network, or to provide resilience to enable the vehicle to ‘limp home’ if the battery is depleted and the vehicle is outside the UKEMS network.

3.2.4 eHGV for the UK Electric Motorways System

The hybrid architecture is a core part of the UKEMS. The eHGVs will use an electric powertrain with a modest-sized battery (i.e. the size of passenger electric vehicle batteries), a pantograph to connect to the overhead catenary to charge during travel, and an ICE range extender. The specifications of suitable eHGVs for the various phases of the UKEMS rollout are outlined in Table 3. As the network is rolled-out, the size of the range extender will be reduced and by 2040 it will become optional and only needed in the rare cases previously discussed.

Table 3: Proposed eHGV specifications for all phases of the UKEMS rollout.

				Range Extender		
Rollout Phase	**Battery Capacity [kWh]**	**Electric Motor Power [kW]**	**Pantograph System**	**Fuel Source**	**Power [kW]**	**Fuel Tank Size [L]**
Phase 1	100	315	Yes	Diesel	150	100
Phase 2	100	315	Yes	Diesel	150	100
Phase 3	80	315	Yes	Diesel	100	50

3.3 Previous Overhead Catenary Lorry Projects

The German and Swedish governments both support the overhead catenary technology. They have both implemented pilot schemes to 'de-risk' their implementations and to prove the viability of the system on public roads. Indeed, in 2017 the German and Swedish governments agreed to collaborate on the technology and its potential rollout. The pair have since been joined by France in June of 2019 to create a 3-way partnership (Trafikverket 2019). Italy is also currently investigating a catenary lorry project. The Swedish government implemented the world's first trial of overhead line ERS technology on public roads. They completed their demonstrator on the E16 outside Sandviken in 2016. The 2 km section took 11 months to complete from investment decision in June 2015 to the first tests in May 2016. This pilot project cost approximately £10 million, or 125 million SEK (Region Gävleborg 2018). The project has been a success overall, hosting thousands of visitors since its completion.

The German government has spent over £62 million (€70 million) to date on its catenary programme across three main demonstration sites (BMU, 2018). These include the A5 near Frankfurt, the BAB1 near Lubeck and the B462 near Baden-Württemberg. In each of the projects, the planning phase consisted of one year, and the construction took 9 months. The electrified sections range between 6 km and 10 km, with an average per lane-km construction cost of approximately £1.29 million (€1.46 million).

The system has been shown to be adaptable across a range of road layout scenarios and does not impact on car drivers or motorcyclists. In addition, the German project has demonstrated that the majority of the system could be constructed from the hard shoulder and outside of the road boundaries, without any closures of the electrified lane. Only the overhead cable installation required a lane closure, and this work was completed during low impact periods (i.e. night-time). The Swedish and German demonstrators have proven that the catenary system works across a range of real-world road infrastructure scenarios and that there are no technical impediments to a wide-scale rollout. Furthermore, these demonstrators have shown there are no major health, safety, construction, or operating risks.

4. Construction and Transition Process

The case for building a UK catenary network is compelling, providing net-zero emissions, low-cost freight transport and significant UK economic activity. This section discusses how the UK could approach the construction of such a network and transition from diesel fuel to catenary powered vehicles.

4.1 Pilot Project

A critical first step prior to deploying a nationwide catenary network is a pilot project that explores how a UK-wide integrated logistics system (including both long-haul and urban vehicles) would operate. As discussed previously, the core catenary technology is mature, having been demonstrated on public roads in Germany and Sweden. However, there are UK specific issues and opportunities that make a UK-based pilot vital. The proposed pilot project would explore several UK-specific knowledge gaps, including the business case specifics, policy issues, taxation approaches, planning considerations, public attitudes, operational strategies, infrastructure installation approaches, land access issues, energy network implications, supply chain opportunities, vehicle technology options and issues (e.g. double-deck trailers), compatibility with international freight systems and emissions impacts (air quality and CO_2). It is proposed that an integrated set of operational, technical, market and emissions data capture and analytics underpin the entire pilot project. A core output will be a detailed, costed national rollout programme.

The Committee on Climate Change (CCC) mirror the view that a pilot project is beneficial. Shortly after the UK announced its net-zero ambition, the CCC issued its technical work to substantiate the feasibility of such an ambitious target. In their, 'Net-Zero: Technical Report' (2019), they reiterate the need to decarbonise HGV's. Furthermore, they recommended that the UK conducts "trials of zero-emission HGVs with associated infrastructure within the UK".

An example pilot project is proposed to scale the investment necessary in this phase. It is based upon a section of the M180 between the A156 and the M18 in South Yorkshire that experiences high levels of HGV traffic from the major port at Immingham, South Yorkshire. The site is near to several national distribution logistics facilities serving Doncaster and beyond, enabling the integration of long-haul and urban logistics systems to also be studied in detail. The proposed pilot is estimated to cost £80 million for 40 lane-km[3] of electrified motorway. It can be built in less than a year, with the overall project spanning approximately four years. The cost and duration includes all of the work to fill the UK-specific knowledge gaps highlighted above; lowering the cost, minimising the risk, and increasing the speed of any subsequent nationwide-scale projects.

4.2 UKEMS Rollout for Infrastructure and Vehicles

Once the pilot project has been completed and the necessary supply chains established, a rapid UK rollout is possible. It is proposed that the rollout is phased starting with the roads most heavily used by HGVs. Once again, an example is provided to give scale and context to this paper. Figure 4 proposes three distinct phases with the rollout starting in 2025 and expected completion in late 2030s.

[3] A lane-km is defined as one kilometre of one lane on one side of the carriageway, for example a 20 km stretch of motorway requires 40 lane-km to fully electrify the slow lane in both traffic directions.

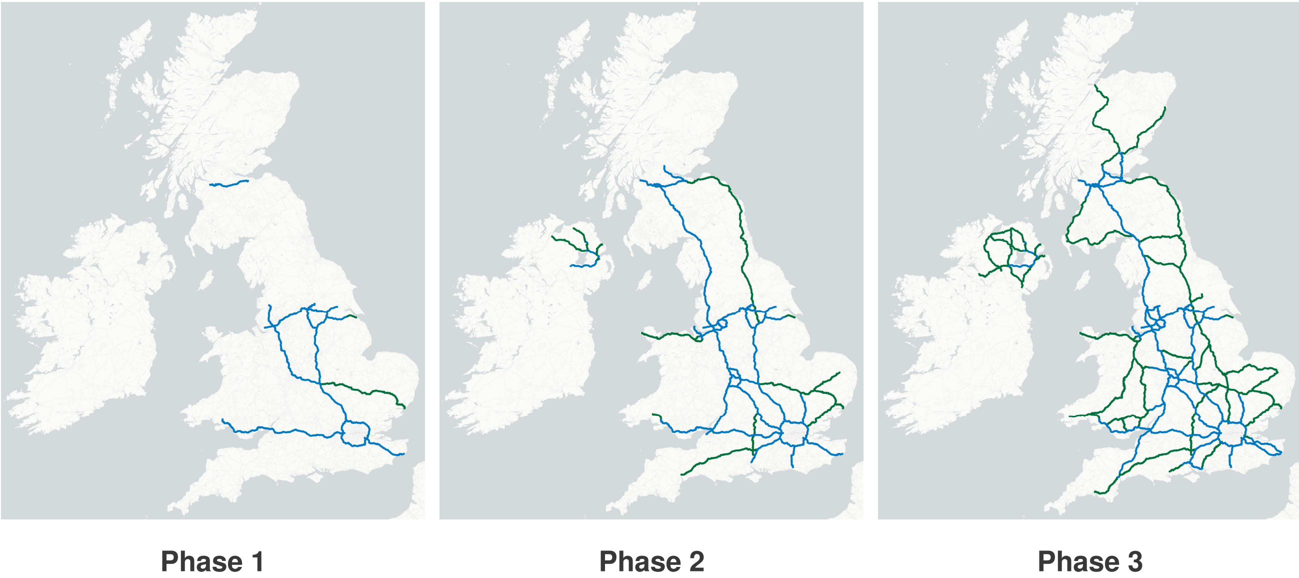


Figure 4: Illustrated example of the 3-phase UKEMS rollout plan for the United Kingdom (motorways are blue, A-roads are green).

Table 4 provides the distances, estimated costs, and CO_2 savings for each of the phases. Further detailed data is provided in Appendix B. The costs are reasonable when compared to other national infrastructure assets or net-zero investments. The distinct phases allow staged investment, with each tranche of capital expenditure providing significant UK coverage and CO_2 benefits. This approach allows risks to be managed and future phases to benefit from the lessons learnt in previous phases. In addition, the scalable nature of this approach supports the UK's achievement of its various Carbon budgets as well as the achievement of net-zero by 2050. By the end of the project, 65% of all HGV-km in the UK will be electric. When combined with the electric vehicles that will be widely used for urban delivery by that time, there will be a very high percentage electrification of UK road freight transport.

The impact of construction on the road network can be minimised through only closing the hard shoulder during the majority of the construction phase. Furthermore, it may be possible to synchronise the construction of the catenary infrastructure with other road investments such as resurfacing work, new barrier installations, and installation of other systems such as the 5G mobile network and vehicle-to-infrastructure systems needed to support Connected and Autonomous Vehicles (CAVs).

Table 4: Summary of the UKEMS construction costs for each of the three rollout phases. For detailed costing information, see Appendix B.

	Phase 1	Phase 2	Phase 3	UK Total (including pilot)
Construction Duration [years]†	2.7	2.6	2.7	8
Number of Build Teams (Number of Construction Workers)††	30 (1,050)	45 (1,575)	60 (2,275)	-
Distance Covered [Lane-km]	3,261	4,759	7,062	15,121
Capital Expenditure per Lane-km [£k]†††	1,500	1,050*	975**	1,113 (UK average)
Total Capital Expenditure [£Bn]	4.9	5.0	6.9	16.8
Estimated Non-Capital Costs [£Bn]+	0.7	0.8	1.0	2.5
Total Costs [£Bn]	**5.6**	**5.7**	**7.9**	**19.4**
% Decarbonisation of UK HGVs [%]++	**31.2**	**18.7**	**14.6**	**64.8**
HGV Carbon Saving whilst on Catenary [$MtCO_2eq^{\#}$]	6.46	3.87	3.01	13.4

† The overall project duration will be significantly longer due to time needed for planning, design, procurement, etc.
†† Includes number of people required for construction of the UKEMS infrastructure only.
††† Includes a small allowance of £100k/lane-km to purchase land for site transformers.
* Assumes 50% of grid connections are cost-shared with car charging.
** Assumes 50% of grid connections are cost-shared with car charging and a reduced transformer cost due to lower traffic levels on Phase 3 roads.
+ Based on 5% for front-end loading activities (CII 2020) and 10% for detailed engineering and project execution.
++ Only accounts for journeys on the catenary – further decarbonisation possible depending on the energy source used when outside the catenary network. Based on HGV count statistics (DfT 2018b).
# Derived from the % decarbonisation and the total HGV CO_2eq emissions as quoted in 'Final UK greenhouse gas emissions national statistics: 1990 to 2018' published by BEIS (2020).

5. Business Cases

To be successful, the UKEMS project must be financially attractive for fleet operators, the catenary infrastructure provider, and the UK Government. This section presents simple economic models developed to assess the feasibility of scheme for: (i) the UKEMS infrastructure provider, (ii) fleet operators, (iii) HM Treasury. The analyses are presented in terms of the economic Payback Periods (PP): i.e. the time to recover the investment costs of vehicles and infrastructure. It also considers the electricity tax revenue that could be earned by the Government from UKEMS, relative to the current revenue earned from diesel fuel tax.

Electricity prices and profit margins are subject to debate and forecasts can vary significantly. For this study it is assumed that:

(i) The UKEMS infrastructure operator purchases electricity at a commercial ‘wholesale' price. Wholesale prices of 5 p/kWh and 10 p/kWh are examined in this analysis.
(ii) The UKEMS infrastructure operator sells electricity at a ‘retail' price so that the desired PP of 15 or 20 years can be achieved for the infrastructure investment, based on revenue generated from electricity sales.
(iii) The Government charges an energy tax in addition to the infrastructure provider's price, so that vehicle operators' investments in their electric vehicles will be paid back in 1.5 years. This should be sufficient incentive to ensure that all fleet operators will switch to electric long-haul vehicles.
(iv) Increasing the ‘retail' electricity price further offers flexibility for both the UKEMS infrastructure operator and the Government to generate additional revenue, but may adversely affect take-up by fleet operators.

Some noted limitations of the financial feasibility studies presented here are:

(i) All costs and prices are in 2020 pounds (£).
(ii) Discounting is applied for the infrastructure provider due to the long time period involved (15 or 20 years). However, the results presented for the fleet operator do not include inflation (no discounting applied) or the structure of investments.
(iii) The vehicles assumed to use the UKEMS are UK-registered long-haul articulated vehicles with Gross Vehicle Weights (GVW) greater than 31 tonnes. The number of potential UKEMS vehicles is likely to be greater than this, with the addition of smaller rigid HGVs, buses and coaches.
(iv) All suitable UK-registered vehicles are assumed to use the system because the short PP will make it compelling for fleet operators to switch from diesel to electric vehicles.
(v) No account is taken of electricity sales revenue from non-UK vehicle operators.

More complex analyses could take other factors into account to give more precise figures, however, the fundamentals of capital costs of vehicles and infrastructure, and operating costs and revenues due to electricity sales will be the same. It is expected that the broad conclusions of this analysis will be robust to the addition of further detail.

5.1 Infrastructure Provider Business Case

The UKEMS infrastructure provider needs to obtain a return on their investment within a reasonable time, however, the scale of the costs and timeframe are greater than for fleet operators and it is appropriate to discount the value of money over time in this analysis. Two different PPs of 15 and 20 years are used as benchmarks for the infrastructure provider, with the aim of estimating the lowest possible electricity sale price (profit margin) through which the PP can be achieved. Table 5 summarises the costs and numbers of eHGVs assumed for the UKEMS infrastructure provider's business case.

Table 5: Input parameters for the UKEMS infrastructure provider business case.

UKEMS Infrastructure Parameters	Value	Source
Total Cost of UKEMS infrastructure†	£19.3 billion	Table 4
Capital Cost of UKEMS infrastructure	£16.8 billion	Table 4
Annual Infrastructure Maintenance Costs**	2% of Capital Costs	Oeko Institute (2020)
Number of UKEMS eHGVs (>31 t GVW)		
- Phase 1*	85,871	
- Phase 2*	136,388	
- Phase 3*	176,388	
Maximum Payback Periods	15 & 20 years	

† Cost does not include pilot project.
* HGV uptake numbers based on HGV count statistics (DfT 2018b) and total number of licensed HGVs (DfT 2020).
** This value includes the costs for personnel, external services, rent, materials, IT / communication and maintenance vehicles, based on the experience of the German demonstrator projects.

5.2 Vehicle Owner Business Case

HGV operators are cost-adverse to adopting new or alternative powertrain technologies because of their low profit margins. Consequently any alternative vehicle must provide fleet operators with a short PP. This analysis assumes an attractive PP of 1.5 years (compared to a baseline diesel HGV) which would drive rapid and widespread adoption of eHGVs. The eHGV solutions, initially described in section 3.2.4, have slightly different specifications for the various phases of the UKEMS rollout. The key parameters for the financial model of the baseline (diesel) HGV and eHGV solutions throughout the phases are summarised in Table 6 (full details and component costs are provided in Appendix C).

Table 6: Parameters for the vehicle owner business case at phases 1 and 3. See Appendix C for complete details of fleet operator business case.

Parameters	Phase 1	Phase 2	Phase 3
Average Annual Vehicle Distance	100,000 km	100,000 km	100,000 km
Diesel HGV Average Fuel Economy	35.8 L/100 km	34.0 L/100 km	31.8 L/100 km
Diesel Fuel Cost*	1.12 £/L	1.12 £/L	1.12 £/L
Electricity Fuel Cost	To be determined	To be determined	To be determined
Baseline Diesel HGV			
- Purchase Price	£92,200	£87,200	£82,200
- Engine Size	350 kW	350 kW	350 kW
eHGV			
- Purchase Price**	£105,692	£96,942	£83,937
- Electric Motor Size	315 kW	315 kW	315 kW
- On-Board Battery Capacity	100 kWh	100 kWh	80 kWh
eHGV Range Extender			
- Fuel and Size	Diesel 150 kW	Diesel 150 kW	Diesel 100 kW
- Fuel Tank Size	100 L	100 L	50 L
% of Distance Range Extender Used	20%	10%	5%
Maximum Payback Period	1.5 years	1.5 years	1.5 years

* Diesel fuel cost is taken from June 2020 (Global Petrol Prices 2020).
** eHGV purchase price includes the cost of a slow smart charger for the depot and all components for UKEMS operation.

5.3 Business Case Results

The results of the economic analysis for the infrastructure provider and fleet operator are presented in this section. Table 7 presents the infrastructure provider's profit margin required on the sale of electricity to vehicles to achieve the stated PPs. The results show that the UKEMS infrastructure is feasible for private financing with a profit margin on the sale of electricity of 7.07 p/kWh for payback in 15 years, or 6.65 p/kWh for payback in 20 years.

Table 7: Business case results for the UKEMS infrastructure, indicating the required profit margin for the sale of electricity through the infrastructure (in terms of pence per kWh) to achieve the payback periods of 15 or 20 years.

UKEMS Payback Period	Electricity Profit Margin
15 years	7.07 p/kWh
20 years	6.65 p/kWh

Using these minimum electricity profit margins required for the infrastructure provider, an evaluation of the fleet operator business case can be performed. While the eHGV vehicle has a higher purchase price than the baseline diesel HGV, the operating costs are considerably lower due to improved vehicle efficiency and the low cost of electrical energy compared to diesel. The primary difference between the implementation phases is that the vehicle purchase price is expected to drop a little as supply chains are established and electric vehicle production volumes increase.

Without any government intervention, the PP for fleet operators would be very short – a year or less. This means there is headroom available for the government to set an excise tax on the sale of electricity to fleet operators. It is assumed that the level of excise tax is set so that the vehicle operators achieve a 1.5 year PP for their investment in eHGVs. This is sufficiently short to ensure a high take-up of eHGVs by fleet operators, with significant tax revenue. Table 8 shows the maximum allowable electricity excise tax the government could introduce across each implementation phase for different electricity purchase prices, with fleet operators still able to achieve a 1.5year PP.

Table 8: The maximum electricity excise tax (pence per kWh) that can be levied on fleet operators by the government whilst achieving a payback period of 1.5 years for an eHGV across the three phases for different electricity purchases prices.

Infrastructure Provider Payback Period	20 years	20 years	15 years	15 years
Wholesale Price (to Infrastructure Provider)	10 p/kWh	5 p/kWh	10 p/kWh	5 p/kWh
Retail Price (excluding Electricity Excise Tax)	17.07 p/kWh	12.07 p/kWh	16.65 p/kWh	11.65 p/kWh
Phase 1 Total Retail Price (incl Electricity Excise tax)	18.15 p/kWh	19.08 p/kWh	18.23 p/kWh	19.16 p/kWh
Phase 2 Total Retail Price (incl Electricity Excise tax)	20.71 p/kWh	21.17 p/kWh	20.75 p/kWh	21.21 p/kWh
Phase 3 Total Retail Price (incl Electricity Excise tax)	24.55 p/kWh	24.79 p/kWh	24.57 p/kWh	24.81 p/kWh

As eHGVs become increasingly prevalent through the 3 phases of UKEMS introduction, the number of diesel HGVs will reduce across the UK. Consequently the Treasury's revenue from diesel excise duty will reduce. Using the results from Table 8, the potential for recovering lost diesel revenue through introducing an electricity excise tax can be examined. The results are presented in Figure 5. The two left hand subplots correspond to an electricity wholesale price of 10 p/kWh, while the two right hand subplots have a wholesale price of 5 p/kWh. The baseline in 2020 is that 100% of HGVs are diesel and they all pay 58 p/L of fuel tax. This is the 100% bar on the left of each sub-plot. In later phases, the amount of revenue from diesel declines but the amount of revenue from electricity increases.

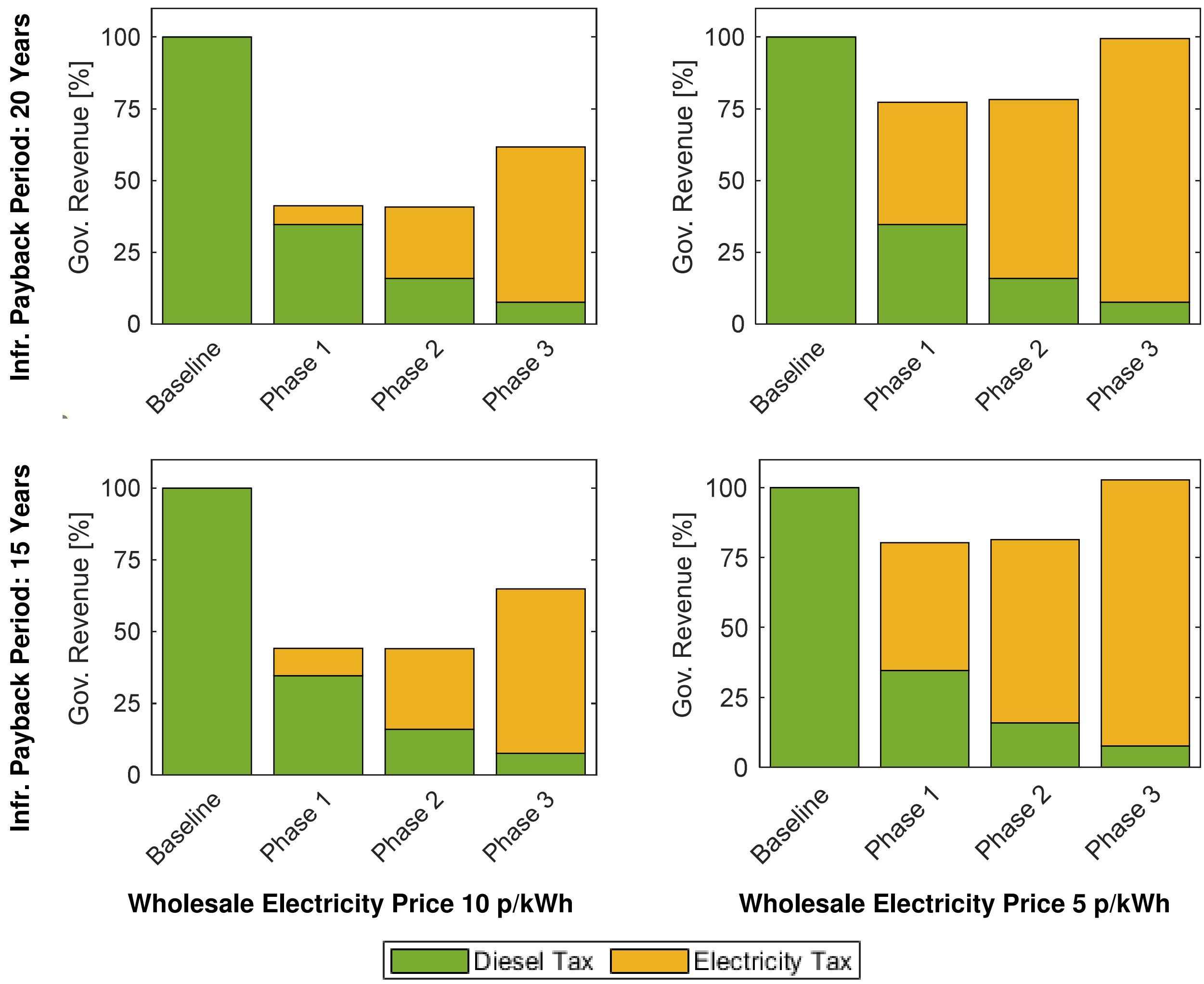


Figure 5: Comparison of the relative Government revenue from diesel and electricity across the different phases of the UKEMS infrastructure for different electricity purchase prices without compromising the 1.5 year payback for fleet operators.

It is apparent that there will be an initial reduction of total tax revenue in the early phases because the revenue generated from electricity tax is less than that lost from diesel. However, as the phases are rolled out there are larger opportunities to raise the electricity duty as electric vehicle costs come down and more vehicles use the UKEMS infrastructure. If the wholesale price of electricity is 5 p/kWh (in the two right-hand sub-plots), the tax revenue after Phase 3 reaches 100% of the current diesel fuel duty. Consequently, the Government does not see any reduction of long-term revenue. If the wholesale price is 10 p/kWh, the Government sees a long-term revenue loss of about 40%. In practice, the wholesale price of electricity is expected to vary with the time of day and the seasons – so the overall financial case is likely to be somewhere between the two columns.

This rudimentary analysis clearly demonstrates the financial feasibility of the UKEMS, and importantly that there is a reasonable amount of headroom available that could be utilised by the UK Government to raise future revenue using an excise tax on electricity, a road-user charge or some other taxation mechanism. Even with these taxes, the system is financially attractive to both fleet operators and long-term private investors in infrastructure projects, with acceptable payback periods.

6. Conclusions and Recommendations

6.1 Conclusions

The amendment to the Climate Change Act in July 2019 mandates that the UK achieve net-zero GHG emissions by 2050. This ambitious target will require a dramatic shift across the UK energy system, encompassing electricity generation, industry, heat, agriculture, and transport. A range of cost-effective and robust solutions will need to be implemented through the 2020s and 2030s to meet the target. One of the most difficult to decarbonise sectors is land-based freight because HGVs require high powers and energies for their normal operations. HGVs transport an overwhelming majority of the UK's goods and create significant proportion of the UK's emissions. It is imperative to replace the de facto standard diesel HGV powertrain with a zero-Carbon alternative. Amongst many considerations, it is vital that energy consumption is minimised alongside decarbonisation, in order to maintain the UK's competitiveness. It is also necessary to adopt a 'shovel ready' solution that can be rolled out quickly.

The UKEMS is an overhead catenary-based infrastructure solution to provide the most efficient and cost-effective use of low or zero-Carbon electricity and decarbonise the difficult HGV freight sector. The technology is mature and several demonstrator pilots have been successfully undertaken in Sweden and Germany. Before the rollout of the large-scale infrastructure project, a 40 km, £80 million pilot project is proposed in South Yorkshire (between Doncaster and Grimsby) to explore the UK-specific knowledge gaps, including business cases, taxation approaches, planning considerations, supply chain opportunities, emissions data and analytics amongst others.

The rollout of the proposed UKEMS network is planned to be carried out through three 2 to 3 year construction phases (each of which will require additional time for planning, design and procurement), that culminate in electrification of over 15,000 lane-km (7,500 km of road) of the UK's major road network. Most of the construction can be done from the hard shoulder, without disrupting the traffic. Once the first phase has been completed, hybrid HGVs will be able to immediately use the network and nearly 50% of all HGV-km in the UK will be electrified. These HGVs would have an electric powertrain coupled with a range extender to deal with transport operations outside of the current network. By the end of the third phase of construction, the UKEMS infrastructure would be sufficiently far-reaching that range extenders could become an aftermarket option for the rare cases where they may be needed (e.g. distribution to remote areas). The solution also extends the electricity grid infrastructure, playing a vital role in supporting the installation of charging points for smaller electric vehicles at motorway services and other locations across the UK; and integrating with provision of 5G and information infrastructure for connected and autonomous vehicles.

Rudimentary financial models were developed to assess the business case for the UKEMS for vehicle owners, infrastructure operator and the UK Government. Despite their limited nature, they clearly demonstrate the UKEMS to be financially attractive for the fleet operators and infrastructure provider within the desired payback periods of 1.5 and 15/20 years, respectively. There is sufficient headroom in the business models for the UK Government to introduce significant electricity excise taxes (or other taxes) – to recoup 100% of lost diesel fuel tax revenues - without compromising the attractiveness of the scheme for vehicle owners or the ERS infrastructure providers. Because of its attractive economics, it is expected that private finance would be interested in funding the infrastructure.

6.2 Recommendations

Based on the findings in this White Paper, the following recommendations are made:

1. The most energy-efficient, cost-effective, economically beneficial, and fastest way to decarbonise the UK's road freight sector is through installation of an electric road system for HGVs. The project could be implemented in a construction period of less than 10 years for a cost of £19.3 billion, which is comparable with the cost of other road infrastructure projects and can be funded by private finance.
2. A pilot project (at an estimated cost of £80million) should be undertaken as soon as possible to identify the UK-specific challenges and opportunities associated with electrification of the road freight sector. The pilot should investigate the following issues:
   - (i) Use a 'living laboratory' approach to test a variety of electrification technology options in an integrated logistics environment: demonstrating how the UK road freight sector could be entirely electrified.
   - (ii) Develop detailed financial models including a thorough sensitivity analysis to investigate the key factors influencing the financial feasibility of the system for freight fleet operators and for infrastructure providers.
   - (iii) Accurately determine the scale of tax revenue generation opportunities for UK Treasury and show how this revenue could be generated whilst maintaining sufficient incentives to enable high levels of take-up of the new technology across the UK freight sector.
   - (iv) Prove the Carbon case for the ERS.
   - (v) Prove the infrastructure, safety and the system resilience of the ERS technology and interoperability across Europe.
   - (vi) Evaluate the network compatibility with other systems such as telecoms (5G) and CAVs.
   - (vii) Demonstrate compatibility with ERS vehicles in different markets (e.g. Sweden, Germany, and Italy), including roaming issues.
   - (viii) Prove that that transition from diesel to electric road freight can be made to work.
   - (ix) Develop a comprehensive, implementable and investable plan to roll out ERS technology across the UK.
3. This project will create a unique opportunity to decarbonise the UK's logistics sector through private finance; to take a leading position in electric roads technology; and to develop the skills and supply chains needed to deploy ERS systems across the country and throughout the EU. This will create green jobs and business opportunities for the UK's fabrication, construction, electrification and vehicle technology sectors.

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Appendices

Appendix A: Technology Readiness Levels

TRL	Description of Level
1	Basic principles observed and reported.
2	Technology concept and/or application formulated.
3	Analytical and experimental critical function and/or characteristic proof-of-concept.
4	Technology basic validation in a laboratory environment.
5	Technology basic validation in a relevant environment.
6	Technology model or prototype demonstration in a relevant environment.
7	Technology prototype demonstration in an operational environment.
8	Actual Technology completed and qualified through test and demonstration.
9	Actual Technology qualified through successful mission operations.

Appendix B: Input Data for Construction and Transition Process

		Source	Phase 0	Phase 1	Phase 2	Phase 3	UK Total
	Distance [lane-km]	GIS analysis of key UK road network	40	3,261	4,759	7,062	**15,121**
Build Time (based upon poles)	Number of build teams		1	30	45	60	
	Catenary poles per day installed	Siemens German exp. up to 5 poles/day on pilot projects	4	4	4	4	
	Distance between poles [m]	Siemens	40	40	40	40	
	Total number of poles		975	81,525	118,975	176,550	
	Build time [work days]		177	494	618	642	
	Years	Assume 250 construction days/year	1	2.7	2.6	2.7	**9**
Unit Costs	Catenary Cost [£k/lane-km]	Based on: Siemens/Ricardo SCAQMD Report, German BMVI Report, CCC Ricardo Report, TRL PIARC report, Siemens German Pilots (German pilot projects)	500	500	400	400	
	Transformers & roadside cabling [£k/lane-km]		500	500	300	225	
	Grid Connection [£k/lane-km]		300	300	150	150	
	Safety Barriers [£k/lane-km]		100	100	100	100	
	Land Purchase [£k/lane-km]		100	100	100	100	
	Total [£k/lane-km]		**1,500**	**1,500**	**1,050**	**975**	**1,113**
Direct Phase Costs	Catenary Cost [£M]		19.5	1,631	1,904	2,825	
	Transformers & roadside cabling [£M]		19.5	1,631	1,428	1,589	
	Grid Connection [£M]		11.7	978	714	1,059	
	Safety Barriers [£M]		3.9	326	476	706	
	Land Purchase [£M]		3.9	326.1	475.9	706.2	
	Total [£M]		**59**	**4,892**	**4,997**	**6,885**	**16.8 Bn**
Indirect Phase Costs	Non-capital costs: capital expenditure	Phase 0 based on detailed plan. Phases 1-3 based on 5% for FEL activities (CII 2020) and 10% for detailed engineering & project execution	0.35	0.15	0.15	0.15	
	Indirect costs [£M]		**20**	**734**	**750**	**1,033**	**2.5 Bn**
Total	Total Costs [£M]		**80**	**5,625**	**5,746**	**7,918**	**19.4 Bn**

Appendix C: Input Data for Fleet Operator Business Cases

The timeline for the component costs for each phase are:

- Phase 1 – 2030.
- Phase 2 – 2035.
- Phase 3 – 2040.

General Parameters

Parameters	Phase 1 Value	Phase 2 Value	Phase 3 Value
Average Annual Mileage [km]	100,000	100,000	100,000
Diesel HGV Average Fuel Economy [L/100 km]	35.8	34.0	31.8
Diesel Cost [£/L] *	1.12	1.12	1.12
Electricity Cost	To be determined	To be determined	To be determined
Depot Smart Charger (22 kW) [£] **	2,500	2,000	1,500

* Diesel fuel cost is taken from June 2020 (Global Petrol Prices 2020).
** From Nicolaides et al. (2019) and assumed to reduce throughout each phase.

Baseline Diesel HGV Parameters

Component	Phase 1 Value	Phase 2 Value	Phase 3 Value	Notes
Baseline Vehicle [£]	70,000	65,000	60,000	Assume 1% yearly cost reduction.
ICE				
Engine Size [kW]	350	350	350	
Engine Cost [£/kW] ***	56	56	56	
Fuel Tank				
Tank Size [L]	300	300	300	
Tank Cost [£/L] *	2	2	2	
Gearbox				
Gearbox Cost [£] *	2,000	2,000	2,000	
Vehicle Efficiency				
Engine [%]	40	42	45	
Drivetrain [%]	95	95	95	
Overall [%]	38.00	40.00	42.75	

* ETI (2016). "Zero emission HDV Database", [spreadsheet] AdHoc_HDV_HD2003_1.xlsm.
*** Ricardo-AEA (2012). *"Review of the efficiency and cost assumptions for road transport vehicles to 2050"*, Ricardo-AEA,

eHGV Parameters

Component	Phase 1 Value	Phase 2 Value	Phase 3 Value	Notes
Baseline Vehicle [£]	70,000	65,000	60,000	Assume 1% yearly cost reduction.
Electric Machine				
Motor Size [kW] *	315	315	315	
Motor Cost [£/kW] **	5.1	5.1	5.1	
Inverter Size [kW] *	347	347	347	
Inverter Cost [£/kW] **	6.4	6.4	6.4	
Battery				
Battery Size [kWh]	100	100	80	
Battery Cost [£/kWh] +	50	42.5	30	
Pantograph				
Pantograph Cost [£]	15,000	12,500	10,000	Author discussions with Siemens.
Range Extender (REX)				
Engine Size [kW]	150	150	100	
Engine Cost [£/kW] ***	56	56	56	
Tank Size [L]	100	100	50	
Tank Cost [£/L] *	2	2	2	
Generator Cost [£]	765	765	510	Same as motor cost factor.
Distance REX Used [%]	20%	10%	5%	
Vehicle Efficiency				
Electric Powertrain Efficiency	87%	87%	87%	
REX Charging Efficiency	45%	45%	45%	Assume peak ICE efficiency.

* ETI (2016). *"Zero emission HDV Database"*, [spreadsheet] AdHoc_HDV_HD2003_1.xlsm.
** Ricardo-AEA (2015). *"Improving understanding of technology and costs for CO2 reductions"*, Ricardo-AEA, Harwell.
*** Ricardo-AEA (2012). *"Review of the efficiency and cost assumptions for road transport vehicles to 2050"*, Ricardo-AEA, Harwell.
+ Based on data from: BloombergNEF (2020). *"Electric Vehicle Outlook 2020"*, [online] available at: https://about.bnef.com/electric-vehicle-outlook/, BloombergNEF, London. (and converting US$1 = £0.79).