How to decarbonise the UK's freight sector by 2050

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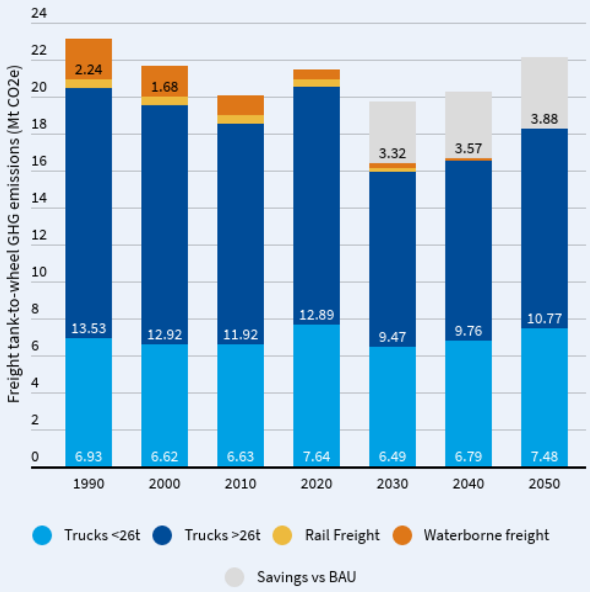
Executive Summary

To achieve the UK’s net zero target, vehicles, including heavy-duty vehicles (HDVs), will need to be entirely decarbonised. The UK government has announced that it plans to phase out the sale of all new cars and vans with engines between 2030 and 2035. It has also announced its intention to consult on a similar phase-out for diesel-powered heavy-goods vehicles (HGVs). This study analyses policies and technologies which can contribute to the decarbonisation of the UK's inland freight sector. It comprises an emissions modelling exercise and a cost analysis for total cost of ownership (TCO) of long-haul trucks. The study shows that for urban and regional deliveries, battery electric trucks offer the best option to decarbonise. It also shows that battery electric trucks and those using an overhead catenary infrastructure are likely to be the most cost-effective pathway to decarbonise long-haul trucks by 2050, but that renewable hydrogen could also be an option.

Efficiency measures such as improved fuel efficiency of trucks, modal shift to rail and optimised logistics supply chains can contribute to reducing freight emissions. But they are not even sufficient to reach the UK's 2030 target, let alone fully decarbonise the UK's inland freight sector by 2050.

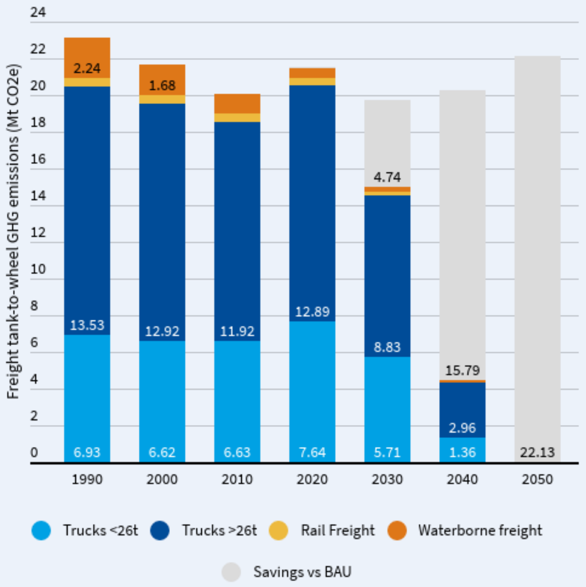
Combining the efficiency measures would result in tank-to-wheel emission reductions of 29% by 2030 and 20% by 2050 against 1990 levels due to increasing freight demand. This is totally inadequate on its own to reach the UK's climate targets. It is therefore necessary to fully decarbonise the HGV fleet. This is technically feasible but to complete the transition by 2050, a start must be made in the early 2020s.



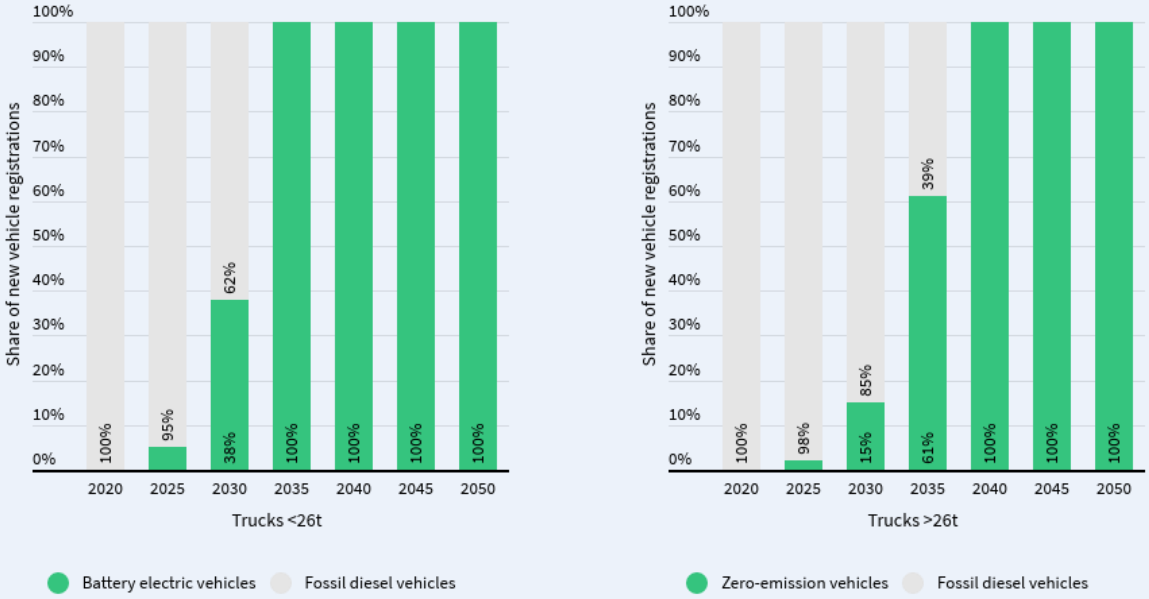
Business-as-usual vs. sum of efficiency measures

In addition to the efficiency measures, an ambitious increase in zero-emission vehicle (ZEV) sales, a 2035 and 2040 sales phase-out for diesel trucks and a ban on the legacy diesel fleet would lead to zero tank-to-wheel emissions by 2050.

ZEV sales will need to reach at least 38% (below 26 tonnes) and 15% (above 26 tonnes) by 2030. The ICE sales phase-out must happen no later than 2035 for trucks below 26 tonnes and before 2040 for heavier vehicles. Even these dates will require a circulation ban on the legacy diesel fleet in 2050 to fully decarbonise the sector. To avoid a circulation ban, earlier phase-out dates will be required.



Efficiency measures, ZEV uptake, legacy fleet ban



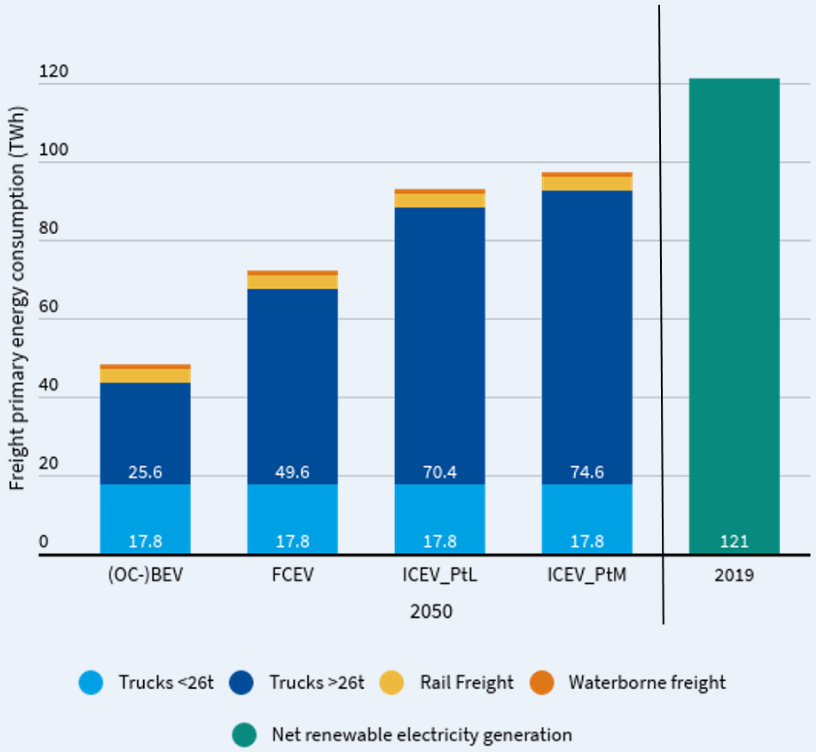
Required uptake rate of new vehicle sales

The powertrain technologies, or *pathways to zero*, which can technically achieve this, include:

1. direct electrification through overhead catenary and battery electric vehicles
2. hydrogen-powered fuel cell electric vehicles,
3. internal combustion engine vehicles fuelled by synthetic liquid or gaseous electrofuels.

All the pathways above rely on renewable electricity from additional generation capacity and can be regarded as GHG-neutral from a well-to-wheel perspective. They are subject to different conversion efficiency losses and the hydrogen pathway therefore requires about twice as much green electricity.

Direct electrification will remain today and in the future, at least twice as efficient as hydrogen and around three times as efficient as internal combustion engines running on synthetic electrofuels. This has an impact on the amount of renewable energy needed for the different pathways. In 2050, the direct electrification pathway would require an equivalent of 40%, the hydrogen pathway of 60% and the two hydrocarbon pathways of 77% and 80% compared to the 2019 net renewable electricity generation in the UK. A fleet trial of battery electric, catenary and hydrogen options to decarbonise long-haul freight would help resolve questions concerning which combination of technologies is most suitable.



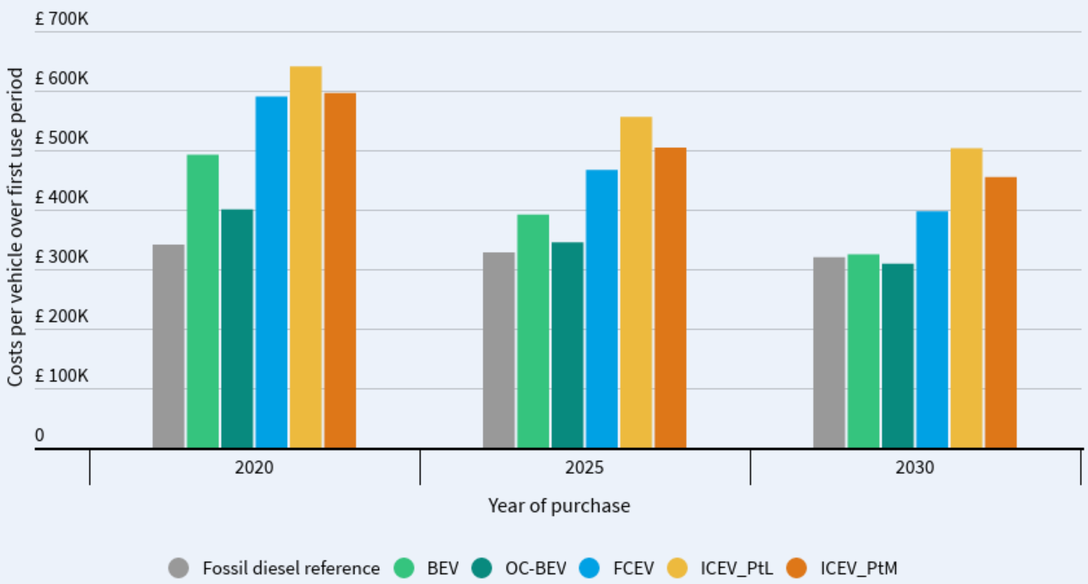
Notes: Battery electrification for trucks below 26 tonnes is assumed across all pathways

Sources: T&E calculations and BEIS (2020).

2050 primary energy consumption compared to the 2019 net renewable electricity generation in the UK

The costs due to renewable electricity are one of several cost components which need to be considered. When factoring in all vehicle purchase, operating and infrastructure costs as well as taxes, levies and road charges, battery electric trucks and those using an overhead catenary infrastructure are likely to have the lowest TCO among all powertrain options.

Total cost of ownership of long-haul trucks in the UK
Electricity-based fuel production in Europe



Policy recommendations

A powertrain transition towards zero emission vehicles for urban, regional delivery and long-haul freight is essential to meet the climate targets at the least societal cost. In order to achieve the UK's goal of net zero emissions by 2050, inland freight transport in the UK needs to be zero emission by 2050. To achieve this, new regulations will be needed and complemented by investment in infrastructure and taxation reform to deliver the transformation.

The Transport Decarbonisation Plan should establish the long term goal of zero emissions in freight by 2050 (not net zero) and concrete policy proposals that will set the UK on a path to achieve this challenging but essential commitment.

Changing from fossil diesel to battery electric vans as well as urban and regional delivery trucks can quickly deliver significant emission reductions. For long-haul freight, battery electric trucks, catenary systems and fuel cell electric trucks running on renewable hydrogen are all credible options at present. However, the uncertainty of how to decarbonise long-haul freight should not delay progress on urban and regional delivery freight where it is clear that battery electric trucks will dominate and progress can be made quickly.

Taxation reform

Road freight transport is a business and for a rapid shift to zero emission deliveries there must be both strong regulation and a business case to transition. A variety of tax reforms can help to improve the economics of zero-emission trucks and help create strong demand for new technologies.

Electricity taxation

There are currently no reduced tax rates foreseen for electricity used in road freight transport. An **exemption from the Climate Change Levy** (£-pence 0.81/kWh since April 2020) is currently granted to the transportation of passengers and goods by train. This provision should be **extended to the transportation of goods by HGVs directly using electricity**, i.e. battery electric trucks and those using an overhead catenary infrastructure. This would help to level the playing field between battery electric and hydrogen trucks as the latter already benefits from a full fuel duty exemption.

Natural gas fuel duty

The UK is currently applying an extremely low fuel duty rate to natural gas used in transport (£-pence 24.70/kg) regardless whether it is fossil-derived or biomethane. A high proportion of the gas supplied to the transport sector today is renewable and there is no reason to offer a duty break to fossil gas. The Treasury should **adjust the reduced rate so this only applies to biomethane** which is sourced from advanced waste- and residue-based feedstocks and which qualifies for the Renewable Transport Fuel Obligation (RTFO). **Fossil gas should be taxed** on an energy content basis **at the same level as diesel**. Biomethane can play a niche role in decarbonising freight but is very unlikely to be able to scale sustainably to play a major role.

Diesel fuel duty

The diesel fuel duty rate has been frozen since 2011. As a minimum, it is essential to **introduce an annual indexation of the fuel duty rate** in line with the Consumer Prices Index (CPI). The historical average inflation rate since 1988 has been around 2.5% annually. Additionally, a **reintroduction of the fuel duty escalator** (raising duty rates at a rate faster than inflation) would progressively equalise diesel fuel duty at 2010 levels and be a powerful stimulus to accelerate the shift to zero-emission trucks. The currently low oil prices are a good opportunity to make progress in this regard.

Supply of zero-emission trucks

National sales phase-out of ICE trucks

The lack of supply of zero-emission trucks is one of the key barriers holding back the market. To address this the UK should **adopt a sales phase-out for new ICEVs with a GVW below 26 tonnes for 2035 at the latest and above 26 tonnes before 2040**. Such a phase-out date can be incorporated into the CO_2 standards or a ZEV target (see below).

CO_2 standards for new HDVs and ZEV sales target

The EU has recently adopted its first-ever CO_2 emission performance standards for trucks. To address the supply gap and ensure that today's available fuel efficiency technology reaches the UK market, the UK government should urgently **transpose the European CO_2 emission performance standards into national law** as it is currently already planning to do so.

Since the current heavy-duty average fleet reduction target for 2030 is insufficient to meet the UK's climate targets, the UK should increase regulatory ambition as soon as possible. One of the most effective and least cumbersome ways to do that would be the **introduction of a mandatory ZEV sales target for 2025 and the following years**. This would oblige manufacturers to sell a certain share of ZEVs as part of their total fleet sales in the UK. The targets could vary depending on the vehicle category and weight class. Such a ZEV target can provide the legal mechanism through which to deliver the sales phase-out for ICEVs with a GVW below 26 tonnes for 2035 and above 26 tonnes before 2040.

In addition to measures to drive the shift to zero-emission trucks, accelerated progress is also needed to reduce the CO_2 emissions from diesel trucks where there remains considerable potential for efficiency improvements. Specifically:

- The **reduction target for 2030 should be increased beyond the current 30%**. A noticeable part of the 2030 fleet reduction target will be met by the increasing deployment of ZEVs, a trend which will continue to intensify in the coming years.
- The **CO_2 standards** and **VECTO** need to be **extended to cover the currently unregulated vehicle types** (trailers and buses) and vehicle groups (other than 4, 5, 9 and 10) to the largest extent which is practically implementable. The UK should **cooperate closely with the EU** in this regard to advance the further development of VECTO.

Vehicle weights and dimensions

The **two-tonne additional maximum weight allowance for ZEVs**, which was introduced by the European CO_2 standards as an amendment to the Weights and Dimensions Directive, needs to be transposed into UK national law. Although the UK will cease to be bound by EU law after 2020, it is strongly recommended to amend the The Road Vehicles (Authorised Weight) and (Construction and Use) Regulation in order to compensate for the currently still higher vehicle weight of battery electric- and hydrogen-powered vehicles compared to diesel trucks.

The same applies to the recent EU Decision setting special rules regarding **maximum lengths for cabs delivering improved aerodynamic performance**. The Decision amends the Weights and Dimensions Directive to allow the exceedance of the maximum vehicle length if the vehicle cab delivers improved aerodynamic performance, energy efficiency and safety performance. This should be transposed into national law as well.

Demand for zero-emission trucks

Purchase incentives

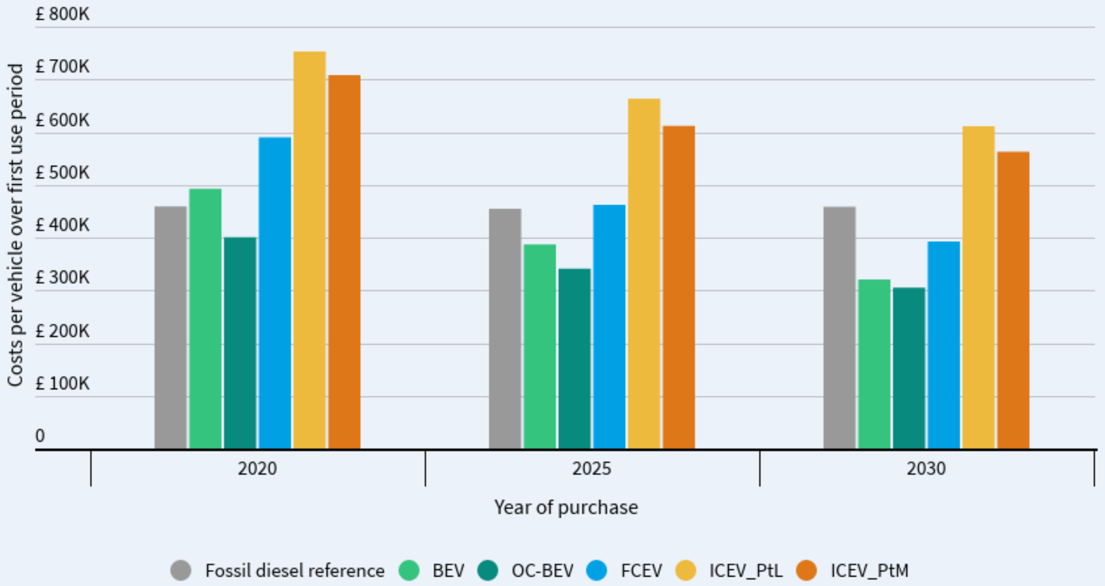
Today's limited availability and higher upfront purchase costs are a significant barrier for hauliers investing in ZEVs despite lower operating costs. In order to incentivise the purchase of ZEVs and accelerate the market uptake, meaningful purchase subsidies will initially be needed. Purchase grants are expensive for the public finances so need to be applied only during the early market phase and be limited to ZEVs. Grants should not be made available for gas-powered trucks as biomethane supply cannot scale to supply a significant share of trucks.

Road charging

Currently, HGVs operating in the UK only have to pay a time-based road charge for the use of the road network. A time-based system fails to deliver the necessary steering effect and fails to encourage either efficient trips or a shift to zero-emission vehicles. It also runs contrary to the user- and polluter-pays principle. With a view to internalise a greater share of externalities caused by trucks and offset the expected future fuel duty revenue decline, the UK government should **introduce a distance-based road charging scheme for all ICE trucks** with a GVW above 3.5 tonnes circulating on UK roads **while exempting ZEVs**. The scheme could subsequently be extended to vans.

Fuel duty indexation and distance-based road charging: impact on the TCO

Maintaining the current plug-in grant and combining it with a diesel fuel duty indexation and the introduction of a distance-based road charging scheme for ICE trucks will accelerate the transition and bring forward price parity with fossil diesel.



Total cost of ownership of long-haul trucks in the UK
Fuel duty indexation and distance-based road charging

Charging and refuelling infrastructure

Funding and financing schemes for private companies

The UK is in the process of rolling out a network of charging infrastructure for electric passenger cars but plans for a suitable charging network for commercial vehicles are largely undeveloped. There is an urgent need to incorporate truck charging into the future Comprehensive Spending Review and National Infrastructure Strategy. The UK government should also consider introducing funding instruments which support transport companies and the logistics sector to install private and shared infrastructure for depot and destination charging for urban and regional delivery trucks.

Such programmes should involve utility companies and provide explicit funding to upgrade the electricity distribution grid, since fleet operators are often unable to bear the additional infrastructure investment costs.

The UK could consider setting up public-private partnerships with vehicle manufacturers and utility companies focusing specifically on public high-power charging infrastructure for regional and long-haul operations along the trunk road network. The upgrade of grid infrastructure alongside the UK's motorway and road network by network operators will also be necessary to roll out high-power charging stations in the megawatt range for battery electric long-haul trucks.

In terms of the deployment of hydrogen refuelling infrastructure for fuel cell electric trucks, targets could be set first for major sea ports to leverage the synergy effects with hydrogen's future role in maritime shipping and exploit its higher cost-effectiveness by cutting down on fuel transport and distribution costs. At this stage the UK could lay the focus on fleet scale trials to test the viability and costs of renewable hydrogen for long-haul trucks.

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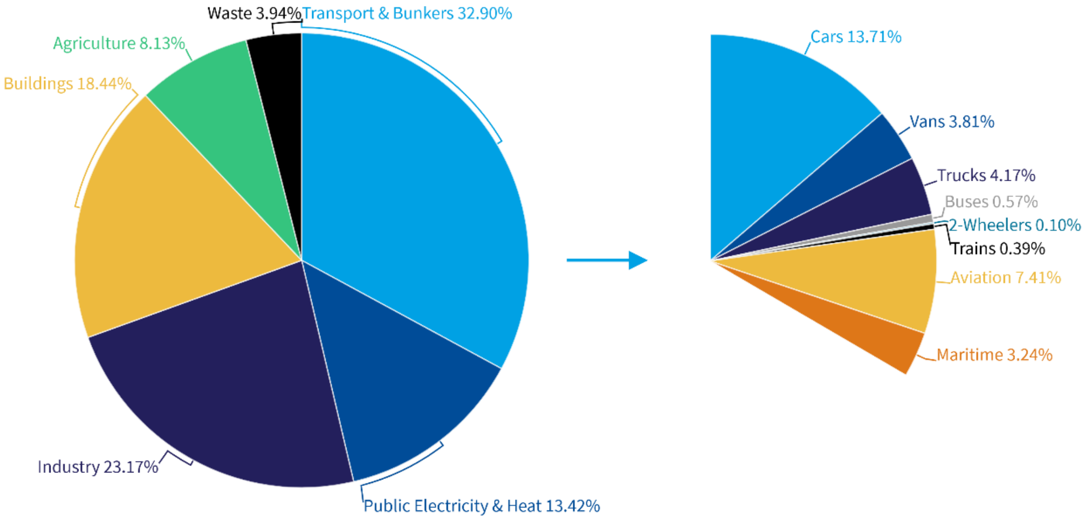
List of acronyms

BEV	Battery electric vehicle
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DAC	(CO_2) Direct air-capture
ERS	Electric road system
EUTRM	European Union Transportation Roadmap Model
FCEV	Fuel cell electric vehicle
FT-synthesis	Fischer-Tropsch synthesis
gCO_2e	Grams of carbon dioxide equivalent
GVW	Gross vehicle weight
GDP	Gross domestic product
GHG	Greenhouse gas
HDV	Heavy-duty vehicle
HGV	Heavy-goods vehicle
HPDI	High pressure direct injection
ICEV	Internal combustion engine vehicle
ICEV_PtL	ICEVs using liquid electrofuels (synthetic diesel)
ICEV_PtM	ICEVs using gaseous electrofuels (synthetic methane)
LCOE	Levelised cost of electricity
LCOH	Levelised cost of hydrogen
LNG	Liquefied natural gas
NECP	National Energy and Climate Plan
OC-BEV	Overhead catenary battery electric vehicle
PtL	Power-to-liquid
PtM	Power-to-methane
PV	Solar photovoltaic power
SMR	Steam methane reforming
TCO	Total cost of ownership
tkm	Tonne-kilometres
TTW	Tank-to-wheel
UK	United Kingdom
VECTO	Vehicle Energy Consumption Calculation Tool
vkm	Vehicle-kilometres
WTT	Well-to-tank
WTW	Well-to-wheel
ZLEV	Zero- and low-emission vehicle

1. Introduction

Transport is the biggest emitting sector in the United Kingdom (UK) with total annual emissions amounting to 124 megatonnes of CO_2 equivalent (Mt CO_2e) and accounting for close to 33% of total 2018 greenhouse gas (GHG) emissions. Road transport represents 68% of all transport emissions including international aviation and shipping, of which around 19% are due to heavy-goods vehicles (HGVs).[1] GHG emissions from HGVs have stagnated in the past and the UK Committee on Climate Change (CCC observed an increasing average CO_2 intensity per kilometre driven in the past years.[2]



Notes: Assuming an 87/13% split between HGV and bus emissions as reported by the Department for Business, Energy and Industrial Strategy. 'Bunkers' stands for international aviation and shipping.

Sources: UNFCCC (2019), BEIS (2020).

Figure 1: 2018 GHG emissions in the UK by sector and transport mode

Under the 2016 Carbon Budget Order which sets the 5th carbon budget, the UK has to reach an overall GHG emission reduction of -57% by 2030 compared to 1990.[3,4] It should be noted that this reduction only amounts to an 80% reduction in GHG emissions by 2050 instead of net zero. After the 2019 amendment of the Climate Change Act, which requires the UK to reduce its GHG emissions by at least 100% until 2050, i.e. net zero, the country must now quickly reduce and, eventually, eliminate GHG emissions from all transport modes by mid-century.[5,i]

Despite fluctuations, transport sector emissions in the UK have been more or less stagnating over the past 30 years (see Figure 2). In this study, a linear reduction trajectory based on the emissions of the transport sector as a whole is taken as the benchmark for inland freight transport. Assuming stagnating emissions between 2018 and 2020 and a linear emission reduction trajectory from 2020 until zero in 2050, the 2030 target amounts to a reduction of -35% against 1990 levels.[ii]

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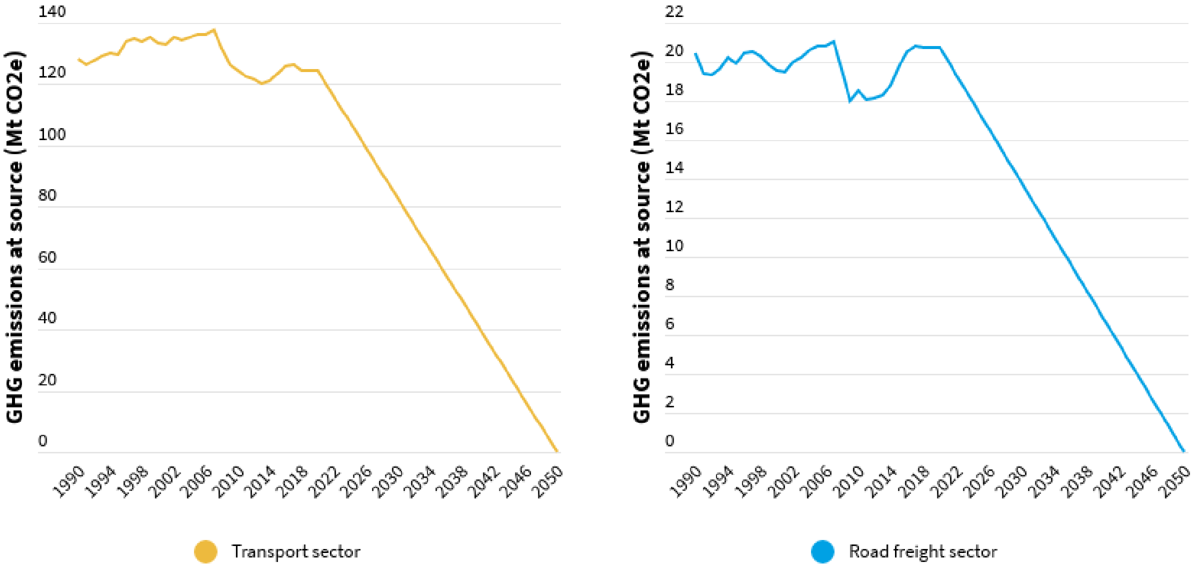
[i] The transport sector will not be able to offset any remaining emissions by using negative emission technologies as these will be required to decarbonise other hard-to-abate sectors such as industry and agriculture.

[ii] Unforeseeable emission reductions in 2020 due to the COVID-19 pandemic were not taken into account.

In concrete terms, this means that the UK needs to reduce inland freight transport emissions (including road, rail and waterborne) from 21.74 Mt CO_2e in 2018 to 15.1 Mt CO_2e by 2030 and zero by 2050.[iii] Failing to quickly reduce inland freight emissions and eventually eliminate them would make the UK's climate targets all but impossible to attain.



Note: Based on the most recent available data from 2018. GHG emissions between 2018 and 2020 are kept constant.

Source: T&E calculations based on BEIS (2020).

Figure 2: GHG emission reduction trajectory

Emissions from the road freight sector pose a major stumbling block to achieve these targets. In 2019, 526,000 rigid and articulated trucks above 3.5 tonnes were licenced in the UK, of which around 426,000 were taxed as 'goods vehicles' (the remaining being exempt from tax or taxed as private HGVs).[6,7] Around 52,000 HGVs are newly registered each year.[8] More than 99% of the vehicle fleet currently runs on conventional fossil diesel.[9] In addition to the domestically registered vehicle fleet, an unknown number of foreign-registered vehicles are moving goods within the UK too.[iv,10] This fleet, and additional vehicles due to the expected increase of future freight demand, will need to be replaced with zero-emission or GHG-neutral alternatives.

The purpose of this study is to analyse instruments and technologies which can significantly contribute to completely decarbonise the UK's inland freight sector. The analysis is divided into the following chapters:

1. Overview of the existing policy measures in the UK
2. Methodology and definition of the business-as-usual (BAU) scenario
3. Efficiency and other measures and their potential to reduce emissions

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[iii] Based on the national GHG inventory submissions to the UNFCCC and assuming an 87/13% split between HGV and bus emissions as reported by the Department for Business, Energy and Industrial Strategy.

[iv] This refers to goods moved from and to the UK by foreign-registered HGVs as well as cabotage within the country and cross-trade. The cabotage freight activity was 1.2 billion tkm, while goods moved from and to the UK amounted to 37.0 billion tkm in 2018 (including the international leg of the trips). This compares to 152.2 billion tkm domestic freight activity by UK vehicles in the same year.

4. Pathways to zero: overview of technologies which are capable to close the remaining gap and help the UK meet its targets
5. Additional renewable electricity demand and cost analysis of the different powertrain technologies
6. Policy recommendations for the UK how to achieve the full decarbonisation of the sector.

As this analysis will show, the so-called *efficiency and other measures* including modal shift and optimised logistics efficiency can contribute but will not be sufficient to reach the targets. There is a need to shift away from fossil fuels to zero-emission or GHG-neutral technology to decarbonise road freight. Liquid and gaseous biofuels are not considered as a viable pathway as there will not be sufficient sustainable feedstock available in the future. As long as there are HGVs circulating on UK roads, they will need to run on clean electricity, whether directly or indirectly in the form of electricity-based fuels. The available technologies require different amounts of electricity and vary in their system and user costs. The options which are identified as capable to fully decarbonise road freight, the so-called *pathways to zero*, need to be based on renewable electricity from additional installed capacity, whether domestically generated or imported:

1. Direct electrification in the form of battery electric and overhead catenary trucks
2. Hydrogen-powered fuel cell electric trucks,
3. Conventional internal combustion engine trucks fuelled by synthetic diesel or synthetic methane.

The options represent the techno-economic context for how the UK can achieve GHG emission reductions of -35% by 2030 and -100% by 2050.

1.1. Adopted policy measures at national level

The UK has yet to introduce meaningful policies to decarbonise its inland freight transport sector. While the UK government has announced a 2030/35 sales phase-out of new petrol and diesel cars and vans, no such date has been adopted yet for HGVs, although a consultation on the phase-out of new diesel HGVs was recently announced.[11] The National Infrastructure Commission has called for banning new sales of diesel-powered HGVs no later than 2040.[12]

In 2018, the government agreed an industry-supported voluntary 15% GHG reduction target for the road freight sector by 2025 (compared to 2015) and it plans to work with industry to develop an ‘ultra low emission standard’ for trucks.[13,14] The 2019 Finance Act brought changes to the HGV road user levy, a time-based road charging system, to incentivise the uptake of cleaner vehicles.[15] Trucks meeting the latest Euro VI emission standard and falling into the highest levy band now pay £ 900, while older, more polluting vehicles pay £ 1,200 annually.[16] The levy has been suspended from 01 August 2020 until 31 July 2021 to help the COVID-19 pandemic recovery efforts.[17]

The country’s draft National Climate and Energy Plan (NECP) mentions the extension of the plug-in grant scheme to large vans and trucks which covers 20% of the vehicle purchase price with a maximum grant rate of £ 8,000 (£ 20,000 for the first 200 orders placed) as well as planned additional national funding of £ 350 million for improving rail freight capacity and capability.[18,19]

Although yet to be adopted, The UK is currently planning to retain the European CO_2 emission performance standards for new heavy-duty vehicles (HDVs) and transpose the regulation into national law without major modifications.[20]

The actions taken to date should begin to reduce emissions but fall well short of what is needed to deliver zero emissions by 2050. This will be necessary for the road freight transport sector if the overall net zero target is to be met.

2. Methodology

The methodology comprises an emissions modelling of the impact of different policies and analysis comparing the costs of long-haul truck powertrains and fuels. The quantification of emissions is undertaken with the *European Union Transportation Roadmap Model* (EUTRM).[21] It is based on the ICCT's *Global Transportation Roadmap Model* (GTRM) and adapted to include the EU Member States plus the UK, Norway and Switzerland.

The EUTRM is a demand driven-model that can compute GHG emissions in yearly intervals between 2015 and 2030, and 5-year intervals thereafter up to 2050. Transport and freight demand are based on the gross domestic product (GDP) adjusted for purchasing power parity, which is determined by historical and projected GDP, population, and fuel prices for each country. All transport demand is then effectively met with unlimited transport capacity. The relationship between freight transport demand and GDP has been observed historically and the assumption that demand shows a decoupling from GDP is carried forward in time (see chapter 2.2). Consequently, an increase of GDP will, to a lesser extent, result in an increase of freight transport demand. Based on the policy measures, this new demand is then met by increasing the HGV fleet through additional new vehicle sales. In the model, freight transport demand does not differentiate for the type of transported goods nor for the transport distance travelled.

The EUTRM is initialised with historical data, whereby HGVs, the vehicle stock and number of new sales, mileage, energy consumption, and load factor are considered. Fleet renewal and vehicle purchasing is based on retirement curves and freight transport demand. In the business-as-usual (BAU) case and with the exception of already adopted policy measures, all of the aforementioned parameters are assumed to remain constant for future years. The only projections made in the model are for GDP, population and demand. Quantifiable policy decisions will change mode-specific parameters. In the case of HGVs, these can include policy driven modal shift, fuel and logistics efficiency as well as powertrain technology uptake. The strength of the EUTRM lies in its ability to combine multiple policy decisions, show their effect on the BAU case, and quantify the relative importance of policies in terms of their tank-to-wheel (TTW) GHG emission reduction potential.

Assumptions made under the untapped potential (UP) scenario should not be understood as explicit policy recommendations but, instead, as hypothetical best-case estimates. The same reasoning applies to the efficiency measures under the BAU scenario. A fleet-wide fuel efficiency improvement in line with the (likely transposed) European CO_2 emission performance standards was included in the sum of efficiency measures. It is important to keep in mind that new sales of zero- and low-emission vehicles will effectively lower the nominal reduction target, both through their counting as multiple vehicles until 2025 as well as through the voluntary sales benchmark from 2025 onwards.

To reduce complexity, the combination of different powertrain technologies is neither considered in the emissions modelling nor in the cost analysis. In the future, a mix of different powertrain technologies may happen to some extent. However, it should be noted that this may have negative implications for the utilisation rate and cost-effectiveness of charging and refuelling infrastructure as well as lower economies of scale for vehicle production and technology development.

2.1. Scope of the analysis

Road, rail and domestic waterborne freight are considered as inland freight transport modes. The movement of goods is measured in tonne-kilometres (tkm) and the movement of vehicles in vehicle-kilometres (vkm). Road freight includes HGVs above a gross vehicle weight (GVW) of 3.5 tonnes. Other commercial vehicles, such as buses, vans and vocational vehicles, are excluded from the scope since they are difficult to compare to HGVs in terms of their application purpose and techno-economic characteristics. Rail freight takes into account both electrified and diesel-powered freight movements. Domestic waterborne freight refers to freight transported by vessels and barges on navigable inland waterways, around the coast as well as to and from offshore locations such as oil rigs and sea dredging.

Due to their predominantly international nature, statistics on international air and seaborne freight pose conceptual difficulties when dealing with them in a manner consistent with inland freight modes and are therefore not included in this study. Transport & Environment has previously published detailed decarbonisation roadmaps for the European aviation and shipping sectors.[22,23]

The EUTRM only considers tank-to-wheel CO_2e emissions. Well-to-tank (WTT) emissions are not further considered in this study. This means that upstream emissions during the production of fuels and electricity are not taken into account in the modelling. This differs to the approach taken in case of the cost analysis. The starting point of all considered pathways in the cost analysis is renewable electricity generated from additional production capacity, either offshore wind in the North Sea or solar photovoltaic (PV) power from North Africa. There is hence no risk of methodological distortion through potential differences in well-to-wheel emissions between the different powertrain technologies.

Emissions in the EUTRM are based on the national GHG inventory submissions to the UNFCCC which are derived from national fuel sales and their allocation to different vehicle classes. Foreign registered trucks circulating on UK territory tend to refuel abroad due to generally higher fuel prices in the UK. The resulting emissions are attributed to the respective country and not to the UK. However, cabotage within the country and cross-trade by foreign-registered HGVs account for a negligible share of territorial freight transport activity. Also, a (smaller) share of UK-registered vehicles is moving goods outside the UK while, at least partly, refuelling in the UK. It is therefore assumed that these irregularities balance each other out.

Although not part of the scope, future well-to-wheel (WTW) and lifecycle emissions of zero-emission and GHG-neutral vehicles will eventually depend on the emissions intensity of the electricity grid and fuel production. The Department for Business, Energy and Industrial Strategy forecasts that the emissions intensity of the UK's power sector will decrease from 173 in 2018 to 41 gCO_2e/kWh by 2035 following the gradual phase-out of the remaining fossil fuel generation capacity.[24] It is expected that the grid will be fully decarbonised until 2050 at the latest in line with the UK's net zero target.

Lifecycle GHG emissions due to vehicle production and end-of-life are not part of the scope either. It is expected that vehicle manufacturing emissions will decrease following the gradual decarbonisation of the power sector and manufacturing processes. The production of battery cells can indeed generate considerable CO_2 emissions depending on the electricity used. The latest research evidence shows that today's carbon intensity of batteries is already much lower than previously estimated.[25] Recent announcements by vehicle manufacturers stress the fact that electric vehicle and battery cell production in Europe will cause near or zero energy-related CO_2 emissions.[26,27,28] It is worth noting that HGVs usually run at maximum possible operation to reduce the total cost of ownership, with lifetime mileages reaching a million kilometres or more in the case of long-haul tractor trailers. Consequently, the carbon intensity per transported tkm attributable to the production of the battery will be modest. The same is true for those emissions resulting from the roll-out of refuelling and charging infrastructure. For example, Wietschel et al. found that the lifecycle emissions from the construction of an overhead catenary system are negligible compared to the well-to-wheel emissions during vehicle operation.[29] A recent study for the European Commission conducted by Ricardo Energy & Environment shows that overall lifecycle GHG emissions of battery electric trucks are consistently lower than those of any other powertrain technology with the exception of electric road systems, today and in the future.[30]

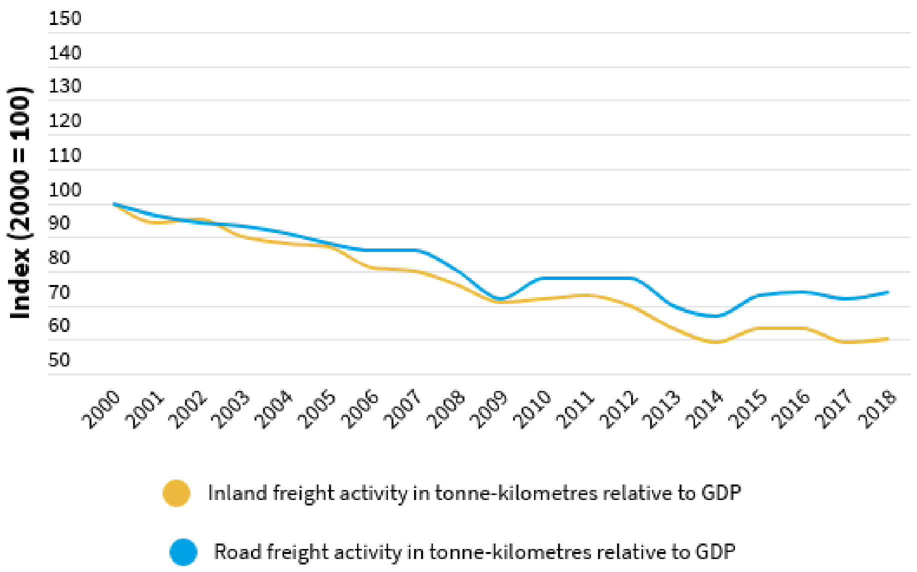
The system and user cost analysis of long-haul trucks is looking into the costs due to vehicle purchase and operation, electricity- and fuel production as well as refuelling and charging infrastructure roll-out and operation. System costs refer to the costs from manufacturing, assembling and selling the vehicle, producing, transporting and distributing the electricity and fuel as well as constructing and maintaining the infrastructure. Except for grid connection fees as well as electricity network and operating costs, which represent the costs due to transporting and distributing electricity, the system costs exclude taxes, levies, road charges and subsidies. This has been a deliberate choice in order to better assess the economic costs for each powertrain technology which need to be borne by the society (manufacturers, operators, consumers and the public sector). By contrast, the user costs, or total cost of ownership (TCO), take into account the current level of taxes and levies on vehicle ownership and final energy products as well as time-based road levies for the use of the UK road network.

A caveat regarding the sum of qualifying efficiency measures should be noted: The sum does not take into account possible interactions and shifts between modes due to changes in freight demand and transport costs, (i.e. *ceteris paribus*). This means that the potential emissions savings disregard that, for example, increased fuel efficiency would result in lower haulage costs and thus lead to higher road freight demand and a higher road modal share. For simplicity, any change in freight transport demand due to price elasticity from electricity and fuel cost changes is not fed back into the emissions modelling.

2.2. Defining the business-as-usual scenario

Assumptions made under the business-as-usual (BAU) scenario need to be viewed with caution, since they are subject to a number of uncertainty factors. Generally speaking, freight transport demand in terms of freight activity is linked to macroeconomic performance, industrial output and trade intensity, albeit this correlation varies among countries and it is unclear how it will develop in the future.[31] In the UK, freight transport intensity - that is freight transport activity in tkm relative to GDP - has been decreasing over the past 20 years (see Figure 3).[32,33] This is to a greater degree caused by a decline in cargo carried by trains and barges than by trucks. Like most industrialised countries, the UK has witnessed a general shift in manufacturing towards emerging and developing countries which was accompanied by declining domestic freight activity relative to GDP over the past decades. Also, the country has been undergoing a relatively swift phase-out of fossil fuel products which used to account for an important share of liquid and dry bulk freight. Fossil-related cargo declined from 52.5 billion tkm in 2008 to 17.5 billion tkm ten years later, while other freight cargo only increased by 12.1 billion tkm during the same period, thereby failing to compensate for the losses.[34] As the decarbonisation of the British economy progresses, the remaining fossil fuel and petroleum volume will disappear altogether.

The current level of freight transport intensity may also not necessarily hold in the future due to other reasons. For example, consumption behaviour may change. Measures to reduce freight demand by changing production and consumption patterns, such as waste reduction, recycling or shorter transport distances, are not further considered in this study in order to assume a conservative estimate of future freight demand, but could help make a contribution to the decarbonisation of the sector.



Notes: The difference between inland and road freight activity is due to a sharper decline of rail and waterborne freight intensity.

Sources: T&E calculations based on ONS (2020) and DfT (2019).

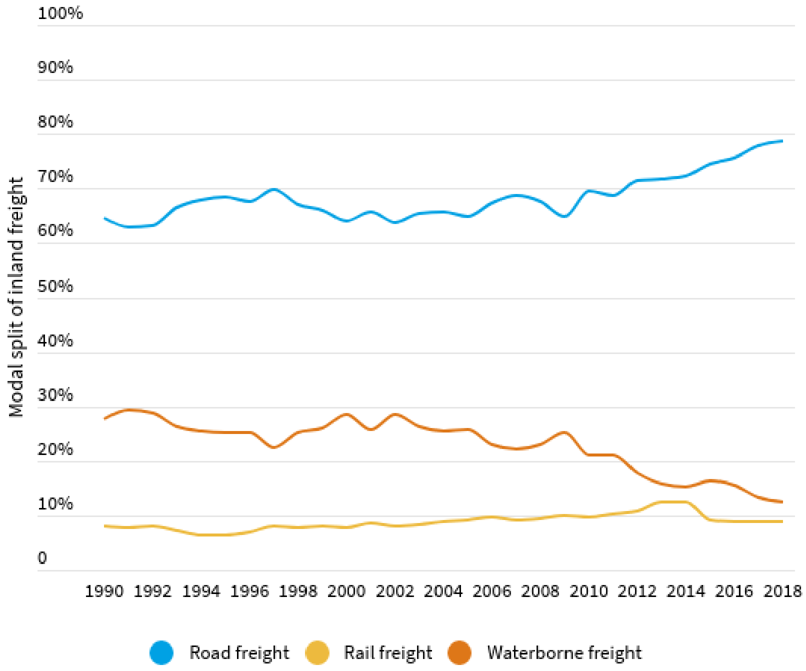
Figure 3: Inland freight transport intensity

The 'UK' always refers to the United Kingdom of Great Britain and Northern Ireland. Fossil fuel prices are kept constant in the model as well as in the cost analysis. In the EUTRM, population projections for the UK are based on the Office for National Statistics.[35] The projection of freight transport demand in the UK is based on the business-as-usual scenario in MDS Transmodal's report 'Future of Freight Demand' which was commissioned by the National Infrastructure Commission.[36] The report uses population projections by the Office for National Statistics and GDP projections by the Office for Budget Responsibility. Table 1 summarises the input data.

Parameter	2018	2030	2050
Population (million)	66.4	71.3	76.9
GDP (£ trillion)	2.1	2.8	4.6
Freight transport demand (billion tkm)	198.3	212.1	253.7

Table 1: Socio-economic assumptions based on MDS Transmodal (2019) and the EUTRM

The relative modal share of rail and waterborne freight has been declining over the past three decades, though it appears to have stabilised recently.[37] As most of the fossil fuel cargo loss has already taken place, it is assumed that rail freight roughly manages to maintain its current relative share in the BAU scenario in the future (see chapter 3.1.2). This is, however, not the case for waterborne freight due to unavoidable structural changes in the type of goods moved (see chapter 3.1.3).



Notes: Excluding inland freight activity of pipelines.

Sources: DfT (2019).

Figure 4: Inland freight modal split

The BAU scenario considers current trends and takes into account all national measures adopted and implemented as of today or those which are expected to be adopted in the near future. This includes all policies listed under 1.2 in as far as they do constitute concrete regulatory instruments which are quantifiable in terms of their emission reduction potential. Figure 5 shows the development of the UK's total tank-to-wheel freight emissions until 2050 under the BAU scenario. Without further action taken, the inland freight sector will see its emissions marginally decrease from 21.7 Mt CO_2e in 2018 to 19.7 Mt CO_2e in 2030 and 22.1 Mt CO_2e by mid-century. Freight transport demand will result in a 28% increase measured in tkm but final energy consumption will increase only by 6% by 2050 compared to 2018.

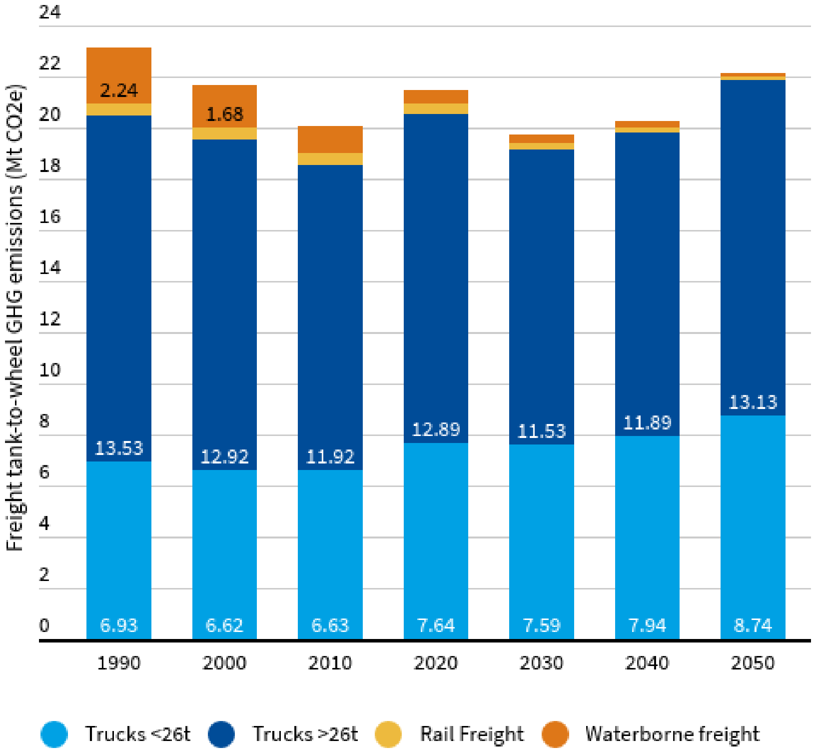


Figure 5: CO_2e emissions of the inland freight transport sector under the BAU scenario

3. Roadmap to zero-emission inland freight

This chapter sets out different measures to reach the UK's targets of -35% by 2030 and -100% by 2050. Chapter 3.1 covers reduction methods using already existing or soon deployable technologies, the *efficiency and other measures*. Chapter 3.2 analyses the different technological pathways which are capable of closing the remaining gap, the *pathways to zero*.

3.1. Efficiency and other measures

There is potential to reduce inland freight emissions by optimising existing technology, through both improving the efficiency of road freight vehicles and the efficiency of the transport system by utilising modal shift and optimising logistics efficiency. *Efficiency and other measures* are in this regard best understood as solutions which are based on conventional technology but whose real-world application requires increased investment in large-scale adoption and infrastructure development. In the following sections the main assumptions for each possible option are presented under a business-as-usual (BAU) scenario and an untapped potential (UP) scenario if applicable. The emission reductions of the qualifying efficiency measures are subsequently added together to assess to what extent they can contribute towards the UK meeting its targets. The remaining gap is then addressed in the subsequent chapters laying out the pathways. The examined efficiency measures are:

1. increased fuel efficiency of trucks
2. modal shift to electrified rail freight
3. modal shift to domestic waterborne freight
4. increased logistics efficiency
5. fossil methane
6. biomethane

3.1.1. Increased fuel efficiency of trucks

There are many different truck types and categories, ranging from urban over regional delivery to long-haul haulage. The fuel consumption of a given vehicle depends on multiple factors including the duty cycle, trailer attachment and respective payload. For the past 15 years, the uptake of fuel efficiency improvements for European trucks has been limited. The average fuel consumption of the new tractor trailer had been relatively stagnant for more than a decade at around 33 L/100 km measured over the VECTO Long-Haul cycle.[38,39] Preliminary vehicle certification data published by truck manufacturers indicates an average fuel consumption of approximately 30 L/100 km in 2019.[40]

Improving the fuel efficiency of new trucks is considered to be an effective measure to curb emissions. Fuel consumption can be reduced by optimising engine efficiency, reducing the aerodynamic drag of both the cab and trailer and minimising rolling resistance by using better tyres. By applying commercially available and prospective, but not yet widely commercialised technologies that will be ready over the next 10 years, it would be possible to make articulated and rigid trucks significantly more fuel efficient by 2030.[41] Such efficiency measures result in fuel savings that exceed their up-front capital costs within payback periods of less than a year, and would therefore lead to substantial net cost savings over the vehicle's lifetime for the first and subsequent vehicle operators.[42]

Under the recently adopted EU Regulation, which is introducing emission performance standards for tailpipe CO_2 emissions, truck manufacturers will be required to reach average fleet emission reductions for certain vehicle groups of 15% by 2025 and at least 30% by 2030 (compared to a 2019/2020 baseline).[43] The CO_2 standards regulate four groups of rigid and tractor vehicles, which account for 77% of new vehicle registrations and 65 to 75% of CO_2 emissions from HDVs according to the European Commission.[44,45] Delgado et al. estimate their share of emissions to be between 80 and 90%.[46] The other vehicle groups remain unregulated for now. The fleet-wide targets can be lowered by a maximum of 3 percentage points through the so-called zero- and low-emission (ZLEV) factor if truck makers deploy a sufficient number of ZLEVs.[v] ZEVs are counted as vehicles with zero tailpipe emissions. Therefore, the higher the number of ZEVs manufacturers will deploy, the more ICEVs with higher reference emissions than 15% and 30% below the baseline they can sell. The CO_2 reference values are simulated on the basis of the Vehicle Energy Consumption Calculation Tool (VECTO).

The UK is not bound by the regulation anymore once the transition period for leaving the EU ends after 2020. However, the UK is in the process of transposing the European CO_2 emission performance standards into national law. Assuming this is completed in time, the UK is expected to match the average EU progress in improving truck fuel efficiency. If the legislation is not implemented, most of the trucks sold on the UK market would come with only limited fuel efficiency improvements, if any at all.

BAU scenario: The UK transposes the European CO_2 emission performance standards into national law. The model therefore assumes that, based on the same regulatory stringency in terms of reduction targets and ZLEV incentive mechanisms, a fuel consumption reduction of around 29% for HGVs above 26 tonnes and 20% for those below 26 tonnes can be achieved by 2030 compared to 2015 based on Delgado et al.[47] Based on the 2019/2020 baseline, this amounts to a reduction of 21% and 11% respectively. The lower value for HGVs below 26 tonnes is due to the fact that rigid trucks up to 16 tonnes GVW are currently outside the scope of the regulation. The reduction values are reasonable when considering that a part of the 2030 fleet reduction target (30%) will be achieved by the deployment of ZLEVs. No further fuel efficiency improvement is assumed beyond 2030.

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[v] T&E calculations.

UP scenario: The potential to increase truck fuel efficiency stated above is likely the upper bound of the technological and cost-effective potential. Further improvements to reduce fuel consumption above that level are therefore not assumed.

3.1.2. Shift to electrified rail freight

Rail currently accounts for 8.8% of the freight transport activity in the UK (measured on a tkm basis).[48] Although rail freight activity has been relatively stable since 1990 with a slight increase from 16.0 billion tkm to 17.0 billion tkm in 2018, it nonetheless experienced a significant capacity reduction of 54% since the mid of the 20th century. In principle, rail freight is significantly more energy efficient and, thus, less carbon intensive than road haulage due to its higher cargo volume per unit, lower rolling resistance and higher share of electrification. 38% of the UK's railway network is currently electrified.[49] This share is expected to increase to 48 to 50% by 2039.[50] The already low tank-to-wheel carbon intensity of rail freight in the UK, currently at 20.2 gCO_2e/tkm, is expected to reach 0 gCO_2e/tkm in 2061 based on electrifying additional network parts with significant freight flows and gradually replacing the diesel stock as explained below.[51,vi] This is in line with the Traction Decarbonisation Network Strategy by Network Rail.[52]

Besides the operational requirement to be able to 'go anywhere' along the rail network, electrification gaps and the non-electrified 'last mile' of rail freight are the main reasons why the vast majority of freight trains in the UK are hauled by diesel-powered locomotives.[53] Due to the fact that freight diesel locomotives reach a life span of 30 years and more, the decommissioning of the rolling diesel stock will take decades without an accelerated phase-out.[54] The diesel rolling stock (including bi-mode) makes up 90% of the total freight locomotive fleet of 856 units, with 75% of the diesel fleet being less than 20 years old while the annual replacement rate for freight locomotives is only around 3.5%.[55] Even if that process began today, it would take at least until 2047 to completely phase out the diesel rolling stock at that pace.

In the case of the currently non-electrified track sections where freight movements are low, battery electric- and hydrogen-powered trains can offer a cheaper solution compared to equipping those sections with overhead lines where service frequencies are too low to reach cost-effectiveness.[56] A recent study on passenger trains has found that higher renewable fuel as well as maintenance and repair costs of hydrogen-powered electric multiple units (HEMUs) result in up to 35% higher costs compared to battery-powered EMUs (BEMUs), whereas BEMUs are barely suitable for non-electrified section lengths of more than 120 km where HEMUs would benefit from their inherent range advantage.[57] It remains to be seen which type of rail freight movements will be carried out by battery- and hydrogen-powered locomotives. The Rail Industry Decarbonisation Taskforce refers to multiple potential issues such as train length constraints in regards to additionally needed fuel-carrying cars and potential payload losses.[58]

Multiple reasons help explain the low rail freight modal share. For distances up to 500 km, moving goods by road is often superior to rail in terms of cost, time, flexibility and adaptability.[59] Likewise, rail freight is highly dependent on the type of goods being transported and more suitable for bulk commodities.[60] Road haulage is the preferred mode for unit load freight and faces few cross-border barriers. Rail track access often needs to be granted up to a year in advance or on a rigid ad-hoc basis due to network planning requirements, which makes it inflexible for just-in-time production and fluctuating demand from shippers.[61]

BAU scenario: The UK has already fully completed its TEN-T conventional rail core network to improve the attractiveness of international rail freight services and increase cross-border interoperability.[62,vii] Few additional national measures are announced to shift freight to rail. Rail freight will also need to make up for the declining bulk cargo market of fossil fuels and petroleum products, although these goods already make

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[vi] The reported figure of 25.3 gCO_2e/tkm in 2018 was adjusted to reflect tank-to-wheel emissions only.

[vii] The Trans-European Transport Network (TEN-T) network and the integrated Rail Freight Corridors (RFC) aim to remove cross-border bottlenecks and facilitate easier long-distance transport in Europe.

up only 14.4% of goods moved in the UK today (2.5 billion out of 17.2 billion tkm).[63] A substantial shift from road to rail does not take place and it is therefore assumed that rail freight will manage to maintain its current modal share of 8.8% in the UK, which nonetheless will lead to an increase of goods moved to 21.0 billion tkm given the increasing freight demand in the future.

UP scenario: Growth potential will only be fully utilised if the infrastructure is improved and rail shipping is made more reliable and flexible, for example by automating and digitising the rolling stock, increasing average train speed as well as length and promoting combined and intermodal transport including ‘rolling motorways’. Road haulage costs will also need to increase to better account for externalities and make rail more cost-competitive.[64]

A report by MDS Transmodal concludes that a considerable shift to rail is indeed possible if favourable rail freight policies, strategic investments, high market growth and inter- and multimodality are prioritised. The report, which was commissioned by Network Rail, estimates that under their central scenario an activity increase to 36.1 billion tkm was achievable provided that there were no infrastructure capacity restraints.[65] The infrastructure project High Speed 2 (HS2) will help free up capacity for rail freight services.[66] The UP scenario therefore assumes that rail freight capacity can be increased from 17.0 today to 36.1 billion tkm by 2050 and kept at that level, resulting in a modal share of 13.6% by 2050. This is equivalent to increasing today’s capacity more than twofold. This shift comes only from HGVs above 26 tonnes because they perform the longest distances.

Although this is in the range of historical peak rail freight activity in the UK, which was 37.0 billion tkm in 1953, it represents a highly ambitious scenario for shifting road freight to rail given that fossil fuels and petroleum products used to account for the bulk of goods moved by rail back then. Also, rail freight has suffered relative losses of competitiveness vis-á-vis road freight since the 1950s due to increases in payload and speed limits of HGVs, the development of the motorway network and structural shifts in industrial production patterns.[67]

Besides faster electrifying additional parts of the network with significant freight flows which are yet to be equipped with overhead lines, it is assumed that a faster phase-out of the diesel rolling stock by 2040 (4.5% annual replacement rate) and its replacement with battery- and hydrogen-powered locomotives takes place in line with the scenarios by Network Rail and recommendations from the CCC.[68,69] The mode consequently reaches 0 gCO_2/tkm tank-to-wheel emissions in 2040 already.

3.1.3. Shift to domestic waterborne freight

Domestic waterborne freight currently accounts for 12.5% of the modal split based on tkm.[70] In the UK, waterborne freight refers not only to goods moved by barges and seagoing vessels on navigable inland waterways but also to those moved around the coast as well as one-port traffic to and from offshore installations such as oil rigs.[71] In 2019, coastwise and one-port traffic accounted for 95% of total waterborne activity, whereas only 1.6 billion tkm were moved on inland waterways.[72] The total volume of activity decreased from 67.0 billion tkm in 2000, when it reached its historical peak, to 25.2 billion tkm in 2019, amounting to a reduction of 64% in just two decades. This can be mainly explained by the decline in coastwise and one-port liquid bulk movements, with fossil fuels and petroleum products still making up close to half of total waterborne freight activity today.[73] It is expected that the remaining waterborne fossil fuel cargo will disappear altogether in the long-term. Based on the BEIS data, it is assumed that the adjusted tank-to-wheel waterborne freight emission factor decreases from 40 gCO_2e/tkm in 1990 to 25 gCO_2e/tkm in 2018 and further to 12.5 gCO_2e/tkm in 2050.[74]

Like rail, waterborne transport offers the opportunity to shift freight activity away from the road. It is not only less carbon intensive but can bring about reduced air pollution, increased safety and potential cost savings. Yet, it suffers from similar structural disadvantages in terms of cost, time, flexibility and adaptability as is the case for rail freight. For waterborne transport to be time-effective and economically viable, significant and continuous infrastructure investment in the network is required. Already existing waterways need to be repeatedly dredged and waterway infrastructure facilities operated and maintained.[75] Waterborne freight is also largely confined to the transport of bulk commodities and, to a lesser extent, standardised container transport. It is subject to even stronger geographical limitations than it is the case for rail freight. This is especially the case for the UK where navigable inland waterways offer very limited, if any, potential to increase capacity.

The technology for zero-emission shipping has been put into practice today in Norway and Denmark and concept barges have been developed in the Netherlands.[76,77,78] Stringent operational CO_2 and zero-emission port standards will be required to drive this technology change towards electrification and renewable hydrogen.

BAU scenario: Negligible national measures are announced or planned to boost waterborne freight. The liquid bulk freight activity of fossil fuels and petroleum products accounted for 43% of waterborne freight activity in 2018 (10.4 billion tkm).[79] In the long term, the remaining fossil fuel volume from one-port traffic will disappear altogether and will only be partly compensated through increased cargo from, for example, constructing offshore wind installations. From 2030, it was therefore assumed that liquid bulk freight activity linked to one-port traffic would taper off to zero by 2050. The result is a 50% reduction in waterborne freight activity between 2018 and 2050. Modal share will therefore drop from 12.2% in 2018 to 4.8% in 2050, resulting in 12.2 billion tkm by mid-century.

UP scenario: It is assumed that the decline in coastal freight could be halved and thus free up 5.2 billion tkm from road by 2050, resulting in a modal share of 6.5% by 2050. This shift comes only from HGVs above 26 tonnes because they perform the longest distances. The total vessel fleet will be directly or indirectly electrified through batteries and fuel cells using renewable hydrogen by 2050 which means that the tank-to-wheel emissions factor of all waterborne freight vessels decreases to 0 gCO_2e/tkm by that year.

Figure 7: Infographic BAU vs. UP modal shift

The results of an ambitious modal shift to rail are shown in Figure 7. The change in emission reductions is marginal, with total 2050 emissions projected to be 2% lower than in 2018, or a 4% saving compared to the BAU scenario in 2050.

3.1.4. Increased logistics efficiency

Freight transport demand and, consequently, final energy consumption and emissions can be reduced by optimising freight logistics efficiency and better utilising the existing vehicle capacity. The share of vehicle kilometres driven empty has actually increased in the UK from 27% in 2000 to 30% in 2019, while the average vehicle loading factor has remained relatively stable at around 0.60.[80]

In some cases, empty and underutilised runs cannot be avoided due to technical or operational reasons.[81] Regional trade imbalances and port traffic as well as practical limitations to consolidate consignments will always result in some level of suboptimal utilisation of freight capacity. This is even more the case since today's widespread just-in-time manufacturing favours smaller transport units and requires carriers to respond with flexibility to short-term needs of shippers. It is expected that the current trend towards even more complex supply chains and a greater transport intensity as a result of the internationalisation of production processes will continue in the coming decades.[82] Nonetheless, there is still great potential to reduce freight activity through, for example, cargo consolidation, cube optimisation and floor loading.[83]

One key reason why hauliers can afford empty and partially loaded trucks is the currently low cost level of road haulage. The level is so low because the road haulage sector only partially pays for their external costs through taxes and excise duties. Charges would need to increase significantly in order to meet the user- and polluter-pays principle and cover the externalities which are caused by inland freight to a greater extent than it is the case today.[viii] In regards to the UK, HGVs cause £ 3.00, rail £ 0.80 and waterborne £ 5.50 of external costs per 100 tkm, whereby more than 90% of the resulting total costs are due to road freight.[84,ix] Besides, the diesel fuel duty rate is frozen at £-pence 57.95/L since 2011, while the headline rate has fallen by more than 12% since then, thereby lowering tax revenues both in real terms and as a share of GDP.[85] Moving towards an annual indexation of the fuel duty rate in line with the Consumer Prices Index (CPI), as the Institute for Fiscal Studies is suggesting, would create a strong price incentive for operators to better utilise loading capacity, consolidate consignments and shift volume to rail and waterborne freight.[86] Cost incentives will also make it more profitable to invest in the digitalisation of supply chain processes, facilitate the real-time management of traffic and cargo flows, encourage the pooling and sharing of loading capacity and improve inter- and multimodality.

BAU scenario: No increase of vehicle taxes, fuel duties or road charges for HGVs is planned in the UK. Road haulage costs continue to be kept at a low level and no further incentives are provided to address the underutilisation of vehicles. Supply chains and distribution networks will be, to a limited extent, further optimised which is assumed to lead to a negligible freight transport demand reduction.

UP scenario: To align the current artificially low cost level with the externalities caused by road haulage, vehicle taxes, fuel duties and road charges in road transport need to rise and better reflect the user- and polluter-pays principle. In 2018, the HM Treasury received around £ 4.6 billion in fuel duties from HGVs.[87] This public revenue will diminish and, eventually, disappear altogether in the coming decades as a result of declining fuel consumption and the increasing uptake of zero-emission vehicles.[88] One idea to compensate for this revenue loss in the road freight sector would be to introduce a distance-based road pricing system for HGVs and possibly differentiate it based on the vehicle's performance in regards to wear and tear on road infrastructure, CO_2 emissions, air and noise pollution. With road freight better reflecting its real costs and with further optimised logistics processes, it is assumed that, from 2020 onwards, the amount of vkm performed by empty vehicles could be reduced by a quarter, thus improving the average load factor, and freight transport demand by a total of 5% by 2030 and beyond.

[viii] The required level of increases depends on which external costs are considered as already internalised today. HGVs circulating on the UK road network are currently not explicitly charged for their externalities. Fuel duties and road user levies can be viewed as implicit charges, thereby covering (at least) a portion of the externalities caused.

[ix] It is worth noting that the mode-specific rates also include costs incurred from accidents, congestion and habitat damage, which usually make up around half of total external costs. These partial costs would also be caused by ZEVs in the future. Other cost factors include air pollution, climate (well-to-wheel) as well as noise.

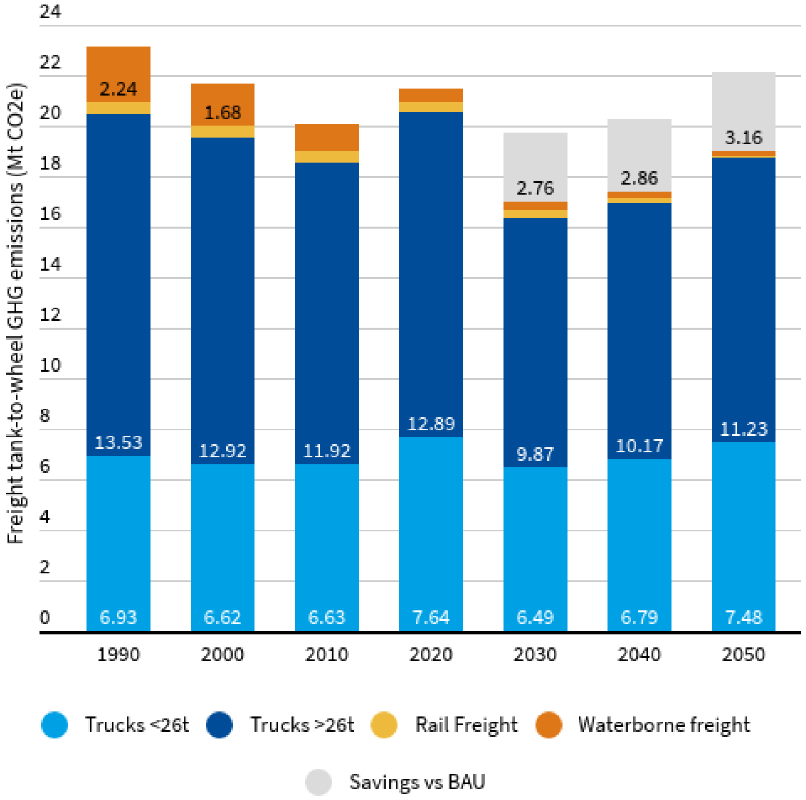

Figure 8: Infographic BAU vs. UP increased logistics efficiency

The results are shown in Figure 8. Increased logistics efficiency leads to a total emissions reduction of 13% by 2050 compared to 2018 emissions, or a 14% saving compared to the BAU scenario in 2050.

3.1.5. Fossil methane

Some industry stakeholders and truck manufacturers see fossil methane as a promising pathway to reduce emissions of HGVs. Methane (CH_4) is the main component of natural gas, which is hereafter called fossil methane or fossil gas in order to differentiate between the different production pathways for fossil-, bio- and power-to-methane. The gaseous fuel can either be compressed or liquefied for storage purposes and combusted in a modified thermal engine to propel the vehicle.

The technical specifications of gas vehicles in the HGV class do not differ, no matter whether the used fuel is derived from fossil-, bio- or power-to-methane production paths, provided that the methane is purified and upgraded for the use in transport. This means that the automotive fuel and combustion characteristics are identical.[89]

Fossil methane in the heavy-duty sector is an ineffective option to reduce GHG emissions. Fossil methane offers only a limited GHG reduction potential on a well-to-wheel basis for a variety of reasons including methane leakage, engine slip and boil-off emissions. In addition, trucks powered by liquefied natural gas (LNG) offer no meaningful air pollutant reductions in terms of nitrogen oxide (NOx) and particulate number (PN) emissions under real-world driving conditions, and may perform even worse than the best-performing diesel vehicles under certain driving cycles, particularly during urban driving.[90,91]

Gas vehicles are commonly equipped with a stoichiometric positive-ignition (PI) or a dual-fuel compressed ignition (CI) engine in combination with high pressure direct injection (HPDI) technology.[92] The dual-fuel engine is primarily powered by methane and uses diesel as secondary fuel to ignite the fuel-air mix.[93]

Compared to diesel, gas translates into an additional fuel consumption of around 10% (CI engine) or 15 to 20% (PI engine), whereas the use of HPDI technology can eliminate these efficiency losses.[94,95,96] The fuel can either be compressed at 200 bar (compressed natural gas, CNG) or cooled down until it liquefies at -161°C to increase volumetric density.[97,98] Storing methane in the cryogenic form leads to a higher energy consumption due to the fuel's liquefaction, transport and distribution which increases the overall production costs.[99,100]

In terms of fossil methane's emission reduction potential, vehicle manufacturers claim CO_2 savings of 10 and up to 20% on a tank-to-wheel basis compared to diesel.[101,102,103] Tests commissioned by the Dutch Government and conducted by the research organisation TNO have shown that tank-to-wheel real-world driving emissions of LNG-powered trucks are between 3% to 10% (PI engines), and 14 to 19% (CI engines with HPDI) lower, depending on the reference diesel vehicle.[104,105,x] Despite this, increased upstream GHG emissions due to methane leakage from the gas supply chain nullify such savings according to recent research findings.[106,107] When factoring in all lifecycle emissions of LNG including those emitted during extraction, processing, liquefaction, transport and distribution, the total savings become negligible in the case of CI engines with HPDI, or can even become negative in the case of PI engines. This is because well-to-tank emission factors associated with imported LNG can be 36% higher than those associated with fossil diesel, primarily due to extracting and liquefying the gas.[108,xi]

In regards to fuel costs, fossil methane is often considered to be an affordable transport fuel. This is in large part due to the preferential tax treatment which the UK is granting to natural gas used in transport. If methane was taxed based on the diesel fuel duty rate, today's natural gas retail price in the UK would not be £ 0.59/kg (excluding VAT) but instead £ 1.07/kg (accounting for the differences in energy content).[xii,109] Given that total lifecycle GHGs from fossil methane are not appreciably lower than those from diesel, there is no conceivable justification for the current tax break fossil methane is benefitting from in the UK.

On the basis of the preceding reasoning, fossil methane fails to qualify as a suitable measure to decarbonise HGVs due to the negligible well-to-wheel emission reduction potential. It is therefore not further considered in this study.

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[x] TNO also included emissions incurred from tailpipe methane slip, tailpipe N_2O emissions, fuel tank boil-off, crankcase venting, leakage and blow-off in their tank-to-wheel calculations.

[xi] Both well-to-tank and well-to-wheel GHG emission factors measured in gCO_2e/MJ-fuel supplied.

[xii] There is no established market price for LNG yet. LNG refuelling stations in the UK either do not communicate prices publicly or charge a politically motivated price. Disregarding the additional costs due to liquefaction, storage and distribution, an LNG retail price in line with the reported CNG retail price of £ 0.71/kg including VAT is therefore assumed. The fuel duty rate for natural gas as a transport propellant is £-pence 24.70/kg (£-pence 1.97/kWh at lower heating value). The fuel duty rate for diesel is £-pence 57.59/L (£-pence 5.78/kWh at lower heating value).

	High-GHG	GHG-neutral
Fossil gas	**Natural gas** produced from both conventional and unconventional sources **Hydrogen** produced from natural gas via steam methane reforming without CCS **Hydrogen** or **power-to-methane** produced from electricity bearing upstream emissions without CCS	**Hydrogen** produced from natural gas in a process that captures and compensates for all supply chain GHGs and process CO_2 through CCS
Renewable gas	**Biomethane** produced from purpose grown-crops with high direct or indirect land-use change (ILUC) emissions	**Hydrogen** or **power-to-methane** produced from additional renewable electricity with zero GHGs and CO_2 from direct air-capture (DAC) **Biomethane** produced from sustainable and advanced feedstock whose avoided methane emissions offset or exceed production and combustion GHGs

Table 2: Gaseous fuels and their definitions based on Searle et al. (2017)[110]

3.1.6. Biomethane

Biomethane, renewable methane largely generated through anaerobic digestion is an effective instrument to reduce GHG emissions from HGV fleets. But availability of biomethane from waste and residues is far too low for a widespread adoption by all HGVs so this subchapter examines the increased use of biomethane as an efficiency measure and not as a potential standalone pathway.

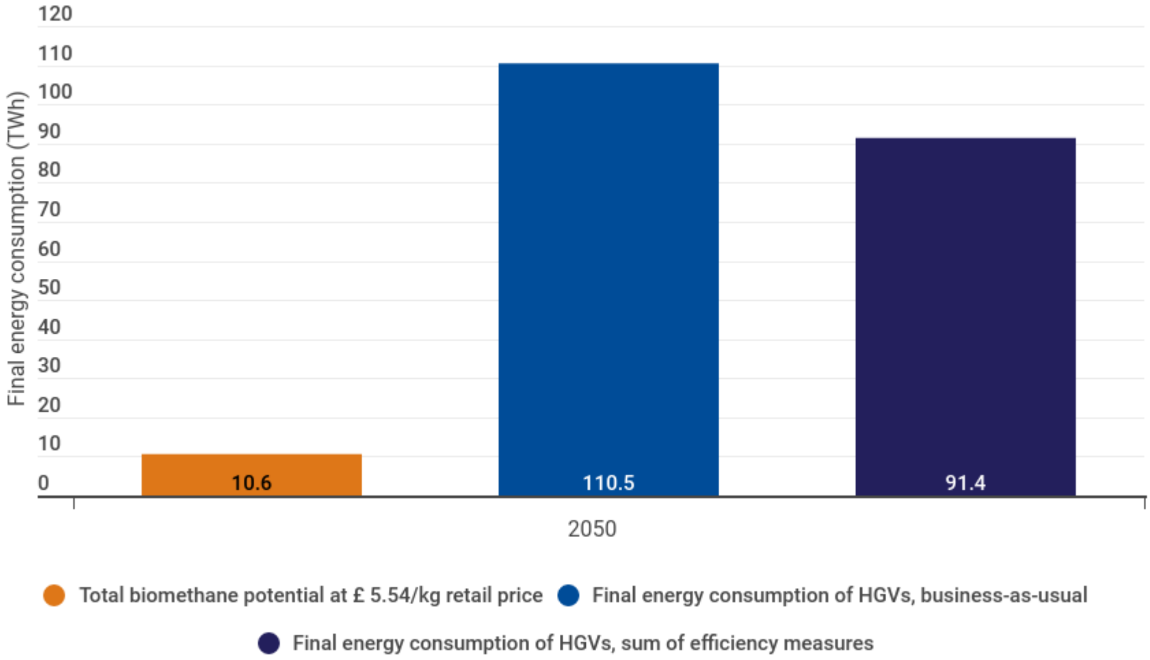
The technicalities of ICEVs using methane as a transport fuel which are discussed in chapter 3.1.5. on fossil methane apply equally to biomethane. This includes engine efficiency, fuel storage, air pollutant emissions and necessary engine adaptations.

Whereas first-generation crop-based feedstocks should not be considered due to their high emissions from direct and indirect land use changes (ILUC) and negative environmental impacts, advanced waste- and residue-based biomethane produced from anaerobic digestion and gasification of biomass can indeed deliver strong GHG reductions if sustainability safeguards are applied (see Table 2). The high production costs and constrained production volume due to limited sustainable feedstock availability will inhibit mass adoption.

The UK's economy-wide primary fossil gas consumption was 967.6 TWh in 2018.[111] All biomethane production in the UK which receives payments under the Renewable Heat Incentive (RHI) programme is exclusively sourced from anaerobic digestion, injected into the national gas grid and then used to generate around 1.0 TWh of heat per year (average between 2011 and 2019).[112] In 2019, a further 0.2 TWh of renewable biomethane was certified under the Renewable Transport Fuel Obligation (RTFO) of which 24.5% were produced from food waste in the UK.[113] Three quarters were imported from other EU countries.

Since the total volume of biomethane production is already coming from waste and residue feedstocks in the form of anaerobic digestion of livestock manure and wastewater sludge, the potential to increase this further in a sustainable manner should be regarded as limited. Searle et al. estimated the maximum sustainable biomethane potential at different cost levels in the UK and concluded that only a low production level would meet the necessary sustainability criteria.[114]

Taking into account total lifecycle GHG emissions, they considered anaerobic digestion of livestock manure and wastewater sludge as well as gasification of biowaste as qualifying feedstock having no or, in part, negative GHG emissions. According to their analysis, the UK could supply a maximum of 10.6 TWh of sustainably sourced biomethane in 2050 at a retail price of £ 5.54/kg_{CNG} excluding additional costs due to liquefaction, distribution and storage.[xiii] This is almost 8 times the average price level of fossil methane in the UK (£ 0.70/kg_{CNG}).[115] For comparison, the final energy consumption, which would be required if the UK's total HGV fleet was running on methane, amounts to 110.5 TWh or 91.4 TWh in 2050 depending on the scenario (see Figure 9). This means that if the entire sustainable biomethane potential in the UK was allocated exclusively to HGVs in the future, it could meet between 10% and 12 % of the fleet's expected final energy consumption in 2050.



Notes: Comparing the final energy consumption of a dual-fual CI HPDI gas vehicle fleet with the total sustainable biomethane production potential in the UK. Assuming that all available biomethane is supplied to HGVs, leaving nothing for the power, industry or buildings sector. Based on a biomethane retail price of £ 5.54/kg, this is almost 8 times the average price level of fossil methane as a transport propellant in the UK.

Sources: T&E calculations based on Searle et al. (2018).

Figure 9: Sustainable biomethane production potential vs. final energy consumption of the PtM pathway

This production volume would only be cost-viable with very high subsidy levels of £ 4.84/kg in order to reach a price comparable to fossil methane. Profit margins in the haulage industry are low and fuel costs make up a large part of the total cost of ownership (TCO). If all this potential was allocated to the transport sector, no volume would be left for the power, industry or buildings sector. This would furthermore imply that current consumers would no longer be able to use it. It should be considered unlikely that a notable share

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[xiii] UK-specific figures for sustainable biomethane feedstock potential were obtained from the authors of the study.

of the sustainable biomethane potential would be allocated to the road freight sector when multiple sectors would be competing for the same limited production volume.

The Department for Transport is currently consulting on relaxing the rules on biomethane imports to the UK. Biomethane is not physically imported into the UK but injected into gas grids in continental Europe or the US which is then piped or shipped to the UK. A system of certificates is used as the transfer mechanism but the current system requires there should be a demonstrable flow of gas to the UK. The consultation proposes to scrap this requirement allowing fossil gas used in UK trucks to claim it is biomethane because biomethane has been produced anywhere else in the world. Now that the UK has left the EU, there are considerable questions how to avoid double counting of biomethane injected into grids in continental Europe or the US and risks of outright fraud. The greater the volumes of biomethane being imported into the UK from increasingly diverse countries the higher this risk becomes.

3.1.7. Summary and remaining gap

Combining all qualifying efficiency measures, and disregarding reciprocal effects between them due to changes in costs and demand (*ceteris paribus*, see chapter 2.1), would lead to significant emission reductions in the UK inland freight sector. The UP scenarios for shift to rail as well as increased logistics efficiency are included in the sum of efficiency measures. As stated above, fossil- and biomethane have been excluded from this due to their negligible emission reduction potential in the case of the former as well as intersectoral competition and non-competitive production costs in the case of the latter.

The results are shown in Figure 10. Compared to 1990, they lead to a reduction in emissions of 29% to 16.4 Mt CO_2e by 2030 and 20% to 18.3 Mt CO_2e by 2050.

Figure 10: Infographic BAU vs. sum of qualifying efficiency measures

While this reduction goes some way to help the UK to meet its 2030 target, the trajectory shows that the qualifying efficiency measures will not be sufficient as it results in a total remaining gap of 16.4 Mt CO_2e in 2030 and 18.3 Mt CO_2e in 2050. It should be noted that some of these efficiency measures, such as a shift to rail, would require significant investment efforts and may not materialise to the degree which was included in the modelling. This makes the decarbonisation of the road freight sector imperative, which will need to be addressed by an increased market uptake of zero-emission or GHG-neutral vehicles.

3.2. Closing the gap: pathways to zero

Even If the sum of qualifying efficiency measures were fully implemented, the UK would fall short of its -35% target by 2030 below 1990 levels. It is clear that increased efficiency and modal shift is not enough as there remains a huge gap to reach zero emissions by 2050. Instead, it will be necessary to decarbonise the HGV fleet, and this transition must begin already in the early 2020s. In the following chapters, the different technologies that can decarbonise road freight are discussed. In the sections hereafter, the final energy demand as well as the overall system costs and total cost of ownership of these technologies are compared.

The *pathways to zero* which technically qualify to bring about full decarbonisation of the vehicle fleet are:

1. direct electrification through overhead catenary and battery electric vehicles (OC-BEVs and BEVs)
2. hydrogen-powered fuel cell electric vehicles (FCEVs)
3. internal combustion vehicles fuelled by liquid synthetic electrofuels (ICEVs_PtL)
4. internal combustion vehicles fuelled by gaseous synthetic electrofuels (ICEVs_PtM)

The first two options require a rapid change and scale-up of new powertrain technology. The third pathway does not require a change of the powertrain technology, as it is a drop-in fuel which would gradually displace fossil diesel. The fourth option requires incremental modifications to the powertrain.

3.2.1. Market uptake and vehicle fleet penetration

In order to decarbonise freight it will be necessary to rapidly increase the share of zero emission or GHG-neutral vehicles. Figure 11 illustrates the fleet penetration rates of new vehicle sales adopted by T&E in its modelling scenarios. For 2035 and 2040, a two-step sales phase-out for fossil diesel vehicles below and above 26 tonnes GVW is adopted. For intermediate years, the share of zero-emission and GHG-neutral vehicles out of total new sales follows an s-shaped non-linear increase which accelerates towards the end. For the vehicle class up to a GVW of 26 tonnes, a market uptake of BEVs only is assumed (see chapter 3.2.2).

It should be noted that, for methodological reasons, the blending of fossil and synthetic diesel is not considered. In the model, ICEVs running on fossil diesel continue to do so for the rest of their lifetime. ICEVs_PtL are exclusively fuelled by synthetic diesel, while ICEVs_PtM run on synthetic methane only.

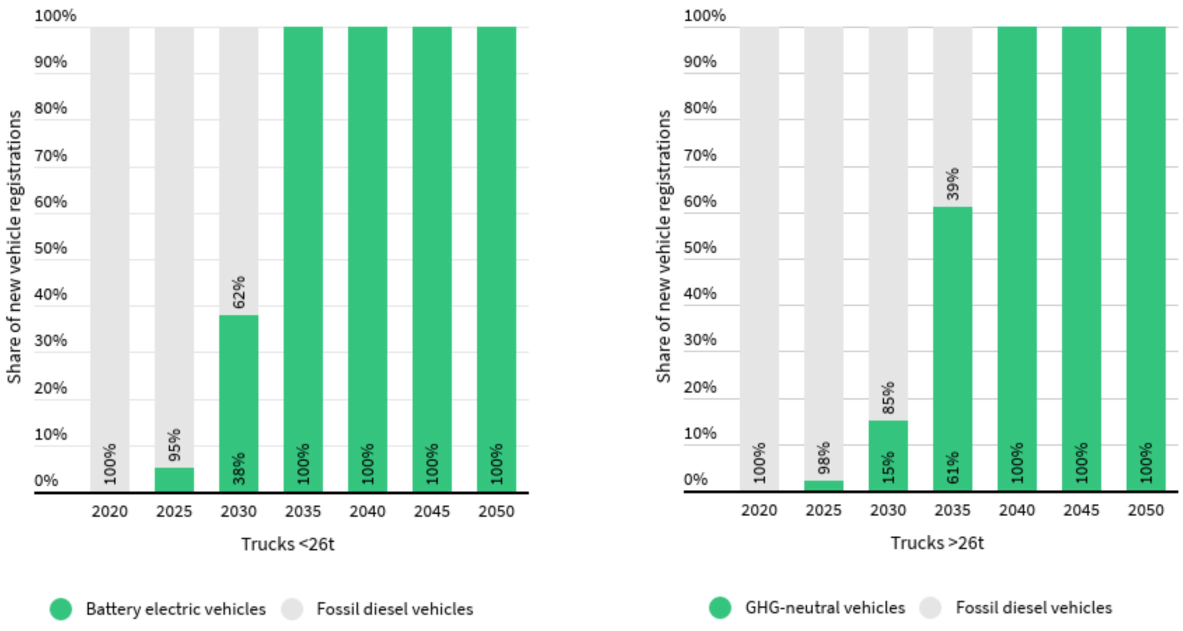

Figure 11: Share of new vehicle registrations

It is assumed that vehicle operations are replaced one for one, which means that load factor and mileage remain unchanged. Because the vehicle survival rates are the same across the pathways, the resulting tank-to-wheel emissions are the same irrespective of the powertrain technology.

It should also be noted that the zero-emission and GHG-neutral vehicle uptake comes in addition to the sum of efficiency measures as described in chapter 3.1. In reality, a part of the nominal 2030 fleet reduction target imposed will be achieved by the deployment of ZLEVs (see chapter 3.1.1).

In terms of the 2030 target, the reduction would amount to a -35% reduction against 1990 levels. Despite a 2035 and 2040 sales phase-out for fossil diesel vehicles, Figure 12 shows that the uptake in zero-emission and GHG-neutral vehicles would not lead to zero GHG emissions by 2050. Instead, a small amount of 0.6 Mt CO_2e would remain due to the legacy fleet which would still be circulating at that time. It would therefore be necessary to enforce circulation limits on the legacy fleet and eventually ban them from the road (except for the ICEV_PtL pathway which would instead require a fossil fuel phase-out, i.e. a 100 per cent blending mandate for synthetic diesel). This would also lead to higher sales of zero-emission and GHG-neutral vehicles in the 2040s in order to cover the unmet freight transport demand. Opting for a phase-out of the circulating legacy fleet would lead to zero GHG emissions in 2050 and a total reduction of 22.1 Mt CO_2e compared to the 2050 BAU scenario.

In 2019, the UK-registered vehicle fleet comprised a total of 334,000 rigid and articulated units below and 192,000 above 26 tonnes. Taking into account the future increase in freight demand and reductions through the efficiency measures including modal shift to rail and increased logistics efficiency, the UK HGV fleet below 26 tonnes is expected to increase to 440,000 vehicles and above 26 tonnes to 260,000 vehicles by 2050.[xiv]

[xiv] It should be noted that this number excludes foreign registered goods vehicles circulating on UK territory as explained in chapter 2.1.

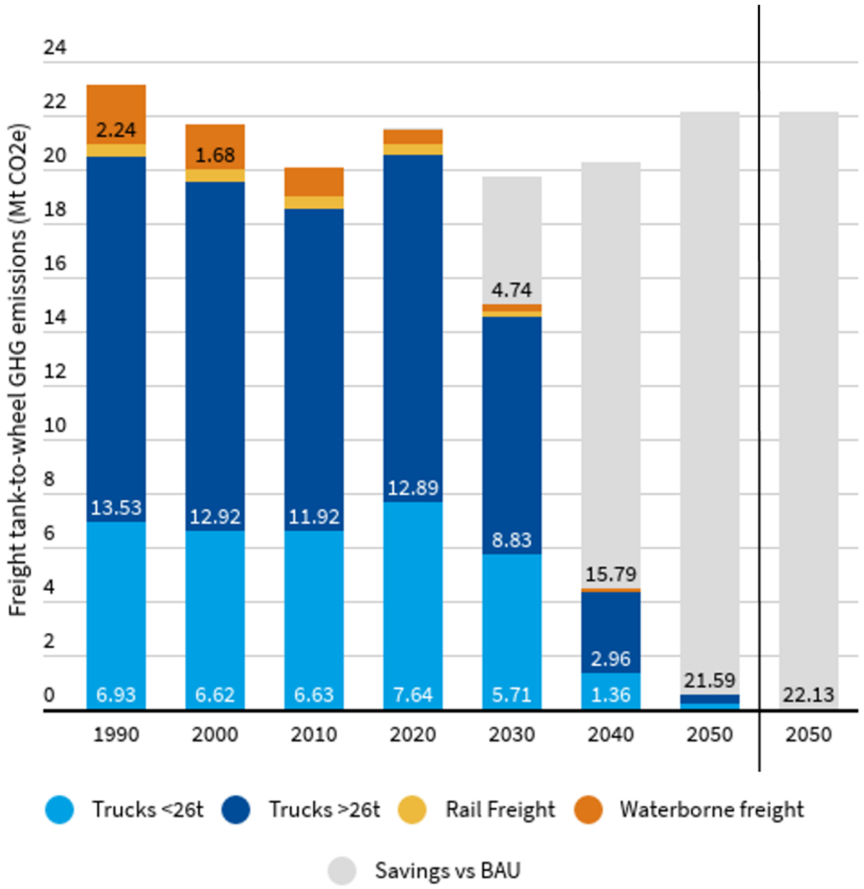

Figure 12: BAU vs. sum of efficiency measures and uptake of zero-emission or GHG-neutral vehicles as per Figure 11. The 2050 column to the right includes a legacy fleet ban

3.2.2. Urban and regional delivery trucks

Depending on their intended purpose, commercial vehicles show differences in terms of their GVW and daily mileage. Lighter HGVs (3.5 to 16 tonnes GVW) are commonly used for urban delivery applications. HGVs with a GVW of 16 to 26 tonnes are mainly used for regional freight transport. Electrified urban- and regional delivery trucks up to 26 tonnes are available on the market today. Examples include Daimler's FUSO eCanter and eActros, Volvo's FL Electric and Renault's D Z.E.[116,117,118,119]

Trucks used for urban and regional delivery operations typically operate within one urban area or perform urban deliveries from nearby distribution centres and return to the depot overnight. Urban delivery trucks have a typical daily mileage of 200 to 400 km, while regional delivery trucks are characterised by single trip lengths of up to 400 km. In the UK, 70% of vkm and 66% of tkm are performed on trip distances of less than 300 km.[120] Direct electrification of these vehicles based on a larger onboard battery is not only technically feasible but, under certain conditions, today already cheaper than fossil diesel from a total cost of ownership (TCO) perspective.[121]

In view of the techno-economic developments as well as market signals from truck manufacturers, it is reasonable to assume that, for the urban and regional delivery vehicles with a GVW up to 26 tonnes, battery electrification will be the most cost-competitive pathway. The model therefore assumes that by 2030 38% and by 2035 100% of HGV sales with a GVW up to 26 tonnes will be BEVs.

3.2.3. Long-haul trucks

Which powertrain technology will prevail in the long-haul sector (26 to 44 tonnes GVW) is less clear. In the following chapter, the pathways are presented which qualify to decarbonise road freight. All of them are at the beginning of the techno-economic learning curve and not (yet) cost-effective. After this section, the vehicle, fuel and infrastructure costs for the different technologies are compared.

3.2.3.1. Direct electrification

Direct electrification has the key advantage of being the most energy efficient, resulting in less primary and final energy use and thus reduced fuel costs. In the case of passenger cars and vans, a large-scale transition towards battery electrification is now widely regarded as the most cost-effective and fastest pathway to achieve full decarbonisation. The production of electric cars and vans is currently ramping up and their market uptake will continue to accelerate.

The development of battery technology is advancing and manufacturing costs are falling. Net battery pack prices have reached a volume-weighted average of £ 117/kWh in 2020 and will further decrease towards £ 49/kWh in 2030.[122] It is expected that the chemical composition of battery cells, that is to say the cathode and anode materials and post-lithium chemistries, will be further optimised, thereby improving the gravimetric energy density, weight, lifetime and longevity of battery packs as well as enabling sustainable raw material sourcing and recycling.[123]

Direct electrification of HGVs, which can take the form of battery electric vehicles (BEVs) and those using an overhead catenary infrastructure (OC-BEVs), provides for superior energy efficiency thanks to well-to-wheel conversion losses of less than 25%. Both use a (differently-sized) battery pack and an electric motor to fuel and propel the vehicle but require different charging infrastructure. Higher vehicle purchase costs due to the onboard battery are compensated for by lower operating costs. Besides the energy efficiency argument, a powertrain directly powered by electricity offers several advantages compared to conventional combustion engines. The vehicle emits no exhaust and thus eliminates CO_2 and air pollutant emissions at the tailpipe.[124] Also, an electric motor is made of fewer components and requires less maintenance and repairs in contrast to an internal combustion engine.

3.2.3.1.1. Battery electrification

The market for BEVs is currently developing. Daimler's eActros LongHaul with a maximum GVW of 44 tonnes and a range of 500 km, and Tesla's Class 8 Semi with a likely similar but yet to be announced GVW and a range of 800 km are expected to go into series production in Europe in 2024 and 2021.[125,126] Nikola's Tre semi-truck with a GVW between 18 tonnes and 26 tonnes and a maximum range of 400 km is planned to enter series production in Europe in 2021.[127]

The energy consumption at the wheels are based on Earl et al. and amounts to 1.44 kWh/km in 2020 and 1.15 kWh/km by 2030.[128,xv] This takes into account vehicle efficiency improvements due to reduced rolling resistance and aerodynamic drag of a 40-tonnes tractor trailer cruising at EU-specific motorway speeds of 80 km/h (50 mph). The average motorway speed of HGVs in the UK is slightly higher at 86 km/h (53.5 mph).[129] This assumption represents a reasonable mean value compared to literature references and industry announcements: Moultak et al. and Sharpe estimate an approximate energy demand at the wheels of 1.6 kWh/km in 2020 and 1.45 kWh/km in 2030 at a U.S.-specific maximum motorway speed of 65 mph (105 km/h).[130,131] Tesla has announced an energy consumption at the wheels of 'less than 1.24 kWh/km' for its Semi truck (also at 65 mph).[132]

[xv] Energy consumption at the wheels determines the onboard energy storage capacity which is required to reach the maximum range without refuelling / recharging. To calculate the electricity consumption (i.e. fuel costs) of the BEV, additional charging losses need to be taken into account. The respective energy consumption values measured from the grid (i.e. 'plug-to-wheel') are 1.52 kWh/km in 2020 and 1.21 kWh/km from 2030.

The drawbacks of battery electric propulsion in the long-haul segment are potential time losses due to longer charging times, the required infrastructure roll-out and, at least at the regional level, the increased power demand on the medium-voltage power grid. Compared to liquid fuels, the lower gravimetric energy density of batteries poses a challenge and could result in reduced payload capacity or range limitations.[133]

Long-haul tractors require a large onboard battery for the required maximum daily range of around 800 km. To achieve this, the BEV included in the cost analysis has a nominal battery capacity of 1,280 kWh in 2020 (decreasing to 1,022 kWh by 2030). The maximum depth of discharge (DoD) is presumed to be 90% which results in a usable battery capacity of 1,152 kWh in 2020 (920 kWh in 2030). The energy density of the onboard battery pack is assumed to increase from 183 Wh/kg today to 318 Wh/kg by 2030.[134] This estimate by Ricardo Energy & Environment is consistent with other projections from the literature.[135] The onboard battery results in a gross additional vehicle weight of 7.0 tonnes in 2020, 4.7 tonnes in 2025 and 3.2 tonnes in 2030. Provided that the UK will transpose the recent changes to the EU Weights & Dimensions Directive into national law, the additional weight would be compensated for by the additional ZEV weight allowance (up to 2 tonnes) under the Directive and net savings from replacing a conventional with an electric powertrain (2.4 tonnes), resulting in a net payload loss of 2.6 tonnes and, consequently, a weight penalty for the BEV in 2020 and 2025. With increasing energy density, this penalty is no longer relevant towards 2030.[xvi] The illustrative calculation below outlines this for the year 2030.

Parameter		Formula	Value	Source
A	Energy consumption at the wheels in 2030		1.15 kWh/km	Earl et al. (2018)
B	Nominal range		800 km	Kühnel et al. (2018)
C	Battery maximum depth of discharge (DoD)		90%	T&E calculations
D	Required nominal battery pack size in 2030	A x B / C	1,022 kWh	-
E	Battery pack energy density in 2030		318 Wh/kg	Ricardo Energy & Environment (2019)
F	Battery pack weight	D / E	3,215 kg	-
G	Weight of electric motor, inverter and gearbox		600 kg	Hall et al. (2019)[136]
H	Total weight of of battery and electric powertrain	F + G	3,815 kg	-
I	Weight of conventional powertrain and fluids in diesel tank		3,000 kg	Sharpe (2019)[137]
J	**Net additional weight of battery electric tractor trailer**	**H - I**	**815 kg**	-
K	Maximum additional ZEV weight allowance under the EU Weights & Dimensions Directive		2,000 kg	European Union (2019)[138]

[xvi] T&E calculations.

L	**Net payload loss of battery electric tractor trailer type-approved in the EU**	**J - K**	**- 1,185 kg**	-

Table 3: Illustrative payload loss calculation. Based on Sharpe (2019)

In terms of charging, long-haul battery electric tractors, whose routes involve multi-day intercity travel, need extensive charging infrastructure along the motorway network. Charging can be done either overnight or through high-power charging points. Recharging times are aligned with EU rules on driving times and rest periods. They foresee maximum daily driving periods of 9 hours (10 hours in exceptional cases) and minimum resting periods of (at least) 9 hours. In addition, mandatory breaks of 45 minutes every four and a half hours are legally required which can be split into two breaks of 30 and 15 minutes.[139] Based on this and an 86 km/h average vehicle speed, one driver can therefore perform a single distance of no more than 387 km between mandatory breaks and a maximum distance of around 800 km per day. Kühnel et al. therefore foresee high-power chargers with an output of 1.2 MW to recharge for a range of 400 km within around 30 minutes and overnight chargers with a power output of 150 kW to fully charge the battery in around 8 hours.[140]

It should be noted that such high-power chargers would place significant additional power demands and require grid connection and likely the reinforcement of the medium-voltage grid. *CharIN*, the vehicle manufacturers' and industry’s standardisation initiative, has started its work on developing a high power charging standard for commercial vehicles (HPCCV) with 2 MW and more.[141] Since the charging times above are aligned with driving times and rest periods, no time penalty due to the loss of operating time is considered.

3.2.3.1.2. Electric road system

Downsizing the onboard battery and charging the vehicle dynamically during operation through an electric road system (ERS) on selected highly-frequented parts of the road network can provide for an alternative to static charging without undermining the efficiency benefits of direct electrification. Both options can be deployed in a complementary approach, thus benefiting the market uptake of BEVs as well as OC-BEVs, since this would also encourage economies of scale and lead to synergy effects in the development of vehicle and charging technology as well as for upgrading the electrical grid.[142]

An ERS is providing the power supply via overhead catenary lines, a conductor rail in the ground, or inductive charging to the electric vehicle, and can offer a cost-effective and complementary solution to electrify the long-haul segment.[xvii] European field trials are currently underway in Germany (overhead lines) and Sweden (one test for each technology).[143,144] Alstom has developed an ERS system with a conductor rail.[145] All three different ERS technologies have their specific advantages and drawbacks, while some regard the overhead line concept as currently the most mature technological option.[146] The overhead catenary technology developed by Siemens and which is currently tested on three parts of the German motorway network was chosen for the cost analysis.[147,xviii] Kühnel et al. provide cost estimations based on, inter alia, the ENUBA projects funded by the German Federal Environment Ministry.[148,149] Recently, the Centre for Sustainable Road Freight published a white paper setting out the roll-out of an overhead catenary network in the UK through the 2030s.[150]

[xvii] Overhead lines can also be used by vehicles with hybrid electric powertrains (OC-HEVs) as it is the case today for the field trials in e.g. Germany. This option was not considered in this study as hybrid diesel vehicles using ERS will likely be an exception after 2030. However, OC-HEVs may play an important role during the early market phase to achieve higher utilisation rates of the overhead catenary infrastructure.

[xviii] The overhead catenary system was also chosen for pragmatic reasons because it provides already for an extensive literature and cost estimations. This is currently hardly the case for the conductor rail system.

The vehicles have a smaller onboard battery which can be charged while the vehicle is drawing power from the ERS and allows for electric autonomy when disconnected from the overhead lines. The OC-BEV included in the cost analysis has a battery capacity between 320 and 256 kWh allowing for a range of up to 200 km when operating disconnected from the overhead lines. According to Wietschel et al., more than 95% of tractor trailer trips off the German motorway are shorter than 100 km.[151] A range of 200 km should therefore be more than sufficient to bridge smaller and larger electrification gaps and the distance between the motorway and the place of (un)loading. In line with Kühnel et al., an electrification degree of 90% was assumed, whereby the remaining 10% is due to gaps within the electrified sections of the network. Taking into account the mileage share on the electrified network (80%), this amounts to a 72/28% mileage split between electricity drawn directly from the overhead lines and from the onboard battery.[152] Ricardo Energy & Environment and the Centre for Sustainable Road Freight estimated a UK network length of 3,600 and 3,150 km respectively by 2050.[153] Consequently, an overhead catenary network of 3,600 km is incorporated in the cost analysis which could cater for up to 130,000 vehicles depending on the utilisation level.[xix]

The energy demand at the wheels of the OC-BEV is identical with the BEV values except for two deviations according to Siemens: The extended pantograph leads to an increased energy consumption of 0.1 kWh/km due to more aerodynamic drag, and higher charging losses amounting to 10% which occur between the medium-voltage grid and the contact wire.[154] The resulting values are 1.54 (2020) and 1.25 kWh/km (2030) measured from the pantograph and 1.72 (2020) and 1.39 kWh/km (2030) measured from the grid. When operating in battery-only mode and with retracted pantograph, the values are the same as for the BEV.

The key market barrier to an ERS is the infrastructure development and, initially, higher capital expenditure costs. The technology needs to be harmonised across Europe and its roll-out well coordinated between all involved stakeholders to ensure cross-border interoperability. Similarly to the charging infrastructure for BEVs, significant additional power demand would be placed on the medium-voltage power grid, possibly requiring in parts grid reinforcements.[155,156]

3.2.3.2. Hydrogen

Hydrogen is considered as an energy carrier whose potential future applications include long-haul road freight. FCEVs are an alternative as they can be zero-emission from a well-to-wheel (WTW) if the required hydrogen fuel is produced from renewable electricity. Nikola plans to produce the Tre also as an electric hydrogen model with a GVW of 40 tonnes and an estimated range of up to 960 km from 2023.[157,158] Hyundai has delivered the first 10 units of the H_2 Xcient to the Swiss market in 2020 which features a 34 tonnes GVW and a range of 400 km.[159] Daimler has announced to enter series production of the GenH2 Truck with a range of up to 1,000 km by the second half of the 2020s.[160]

Besides steam methane reforming (SMR), hydrogen can be produced by an electrolyser which splits water into hydrogen and oxygen using electrical energy. The electro-chemical conversion in the vehicle's fuel cell then generates electricity which propels an electric motor. The advantages include a higher tank-to-wheel efficiency compared to internal combustion engines, short refueling times, no tailpipe CO_2 and air pollutant emissions and potentially long driving ranges. The key challenges are the well-to-tank conversion efficiency losses, the high vehicle technology costs, the low volumetric energy density of hydrogen, the need to develop the necessary distribution and refuelling infrastructure, and an increased likelihood to rely on fuel imports from outside Europe due to a higher renewable electricity demand, as explained in chapter 4.

The energy demand at the wheels is identical for both the FCEV and BEV as they share the same vehicle characteristics and powertrain components with the exception of the fuel cell system and hydrogen fuel tank. The differences between them is due to the additional conversion loss when converting the hydrogen in the fuel cell to electricity (54% conversion efficiency rate in 2020, 56% in 2030 and 61% in 2050).[161] The

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[xix] T&E calculations.

result is a tank-to-wheel energy consumption of 2.53 kWh/km in 2020, 1.95 kWh/km in 2030 and 1.79 kWh/km in 2050. These values also compare well to Moultak et al.[162]

FCEVs have a fuel cell system, a smaller onboard battery pack to buffer energy for engine peak loads and a hydrogen fuel tank with either compressed or liquefied hydrogen. Compression at 350 or 700 bar is the technically most mature and proven storage possibility but has disadvantages in terms of volumetric energy density.[163] Compression at 700 bar offers a higher density than 350 bar and results in lower component costs and conversion losses compared to liquefaction. Liquefying the hydrogen would increase the storage density substantially but would also lead to additional energy losses of 25 to 35% and require more expensive cryogenic thick-walled tanks.[164,165] For the cost analysis, a compressed fuel tank at 700 bar pressure was chosen with a weight between 1.3 and 0.9 tonnes depending on the vehicle's energy consumption and storage capacity. The range of the hydrogen dispenser flow rate is estimated to be between 3.6 and 7.2 kg_{H2} per minute which ensures refuelling times of always less than 20 minutes if the tank is completely empty.[166]

Today, hydrogen is mostly produced from fossil gas through SMR and almost exclusively used in the industry sector. It is also possible to generate it from fossil-derived electricity via electrolysis. Both techniques produce so-called fossil-derived, or ‘grey' hydrogen, with upstream GHG emissions (see also Table 2). Fossil-derived ‘blue' hydrogen requires carbon capture and storage (CCS) which allows for capture rates of 90% of downstream if the most advanced technology (autothermal reforming, ATR) is used.[167] However, around 25% of total natural gas lifecycle emissions are caused upstream which continue to be emitted when producing blue hydrogen.[168] This leaves hydrogen produced from renewable electricity, so-called renewable, or 'green' hydrogen as the only viable production method to achieve zero well-to-wheel GHG emissions.

The idea to use excess renewable electricity to produce hydrogen in situations when renewables need to be curtailed due to grid bottlenecks or supply peaks is disputable. Sources state that this would fail to provide the necessary load factor to operate the production facilities cost-effectively.[169] The lower the degree of utilisation the higher will be the share of investment expenditure as part of the total costs. For a scaled up electrolysis plant in the megawatt range, 2,800 full-load hours are considered realistic in order to provide for a load factor of 30 percent and reach a hydrogen cost level in the range of €-cent 7 to 12/kWh (€ 2.33 to 4.00/kg_{H2}) excluding transport and distribution costs.[170] Today, offshore wind facilities in the North Sea provide between 2,500 and 4,500 full-load hours on average and would therefore be suitable for the production of hydrogen if their total electricity production was devoted to it.[171]

If the hydrogen is to be produced outside of Europe due to electricity cost advantages, it would need to be compressed and transported through an inter-continental hydrogen pipeline network or liquefied and transported via tanker vessel to the UK which would entail considerable energy conversion losses.[172] Other overseas transport options include the use of hydrogen carriers such as ammonia or liquid organic hydrogen carriers (LOHCs).[173] Unless a wide-ranging domestic distribution pipeline network was made available in the future, the UK-wide distribution from a production site or from a port of entry would be handled by insulated cryogenic tanker trucks which can carry and deliver up to 4,000 kg of liquefied hydrogen to the refuelling station where it can be either used directly or gasified again.[174,175] Another option is the decentralised, on-site hydrogen production at the refuelling station from dedicated renewable electricity through a power purchase agreement (PPA), perhaps with temporary electricity storage to reach the required load factor of the electrolyser.[xx]

[xx] The renewable electricity can either be produced on-site as well, or off-site using a PPA.

FCEVs require the roll-out of a network of hydrogen refuelling stations. There are currently 15 low-capacity refuelling stations operating in the UK, of which only one offers hydrogen for buses and none in liquefied form.[176] The exemplary hydrogen refuelling station used for the cost analysis has a capacity of 5,468 kg_{H2}.

3.2.3.3. Power-to-Liquid

Power-to-liquid (PtL), that is to say synthetic diesel produced from green hydrogen and CO_2 through the Fischer-Tropsch (FT) synthesis, could theoretically provide for a GHG-neutral pathway to decarbonise long-haul road freight. The advantages of liquid FT-diesel are the mature and widely commercialised vehicle technology - which would make a powertrain transition redundant - as well as the fuel's high energy density and the established distribution and refuelling infrastructure which could continue to be used. The key challenges are the high conversion efficiency losses during the fuel production process, the comparatively low thermal efficiency of the internal combustion engine, the resulting high fuel costs, the need for air pollutant emission reductions and a greatly increased likelihood to rely on fuel imports from outside Europe due to significantly higher renewable electricity demand.[xxi]

The hydrocarbon-based liquid fuel is produced through the Fischer-Tropsch (FT) synthesis. The process requires hydrogen and CO_2 from direct air-capture (DAC) as feedstock. DAC, i.e. capturing the CO_2 directly from the ambient air, is the only viable method to produce a carbon-neutral fuel. Less-expensive carbon capture and utilisation (CCU) from an industrial point source risks double-counting and can not guarantee a closed CO_2 cycle as it leads to the accumulation of CO_2 in the atmosphere. As it is the case for hydrogen, PtL production plants require a high utilisation rate in order to reach cost-effectiveness. Based on the Agora PtG/PtL calculator, the cost analysis assumes 4,000 full-load hours in combination with temporary hydrogen storage if necessary.[177]

The energy consumption at the wheels (i.e. tank-to-wheel) of vehicles running on PtL diesel takes into consideration the fuel efficiency improvements of the UP scenario, i.e. a reduced fuel consumption of -29% by 2030 for tractor trailers against 2015 levels (29.86 L/100 km in 2020 and 23.47 L/100 km in 2030).

3.2.3.4. Power-to-Methane

Power-to-methane (PtM), that is to say synthetic methane produced from green hydrogen and CO_2 from DAC, could also theoretically provide for a GHG-neutral pathway to decarbonise long-haul road freight. The advantages of power-to-methane are the relatively mature vehicle technology and manageable engine adaptations. Similarly to power-to-liquid, the key challenges are the high conversion losses during the fuel production process, the comparatively low thermal efficiency of the internal combustion engine, the resulting high fuel costs, the lack of meaningful air pollutant emission reductions and a greatly increased likelihood to rely on fuel imports from outside Europe due to significantly higher renewable electricity demand.[178] The low volumetric density of the gaseous fuel in terms of storage poses a further challenge.

The technicalities of ICEVs using methane as the fuel, which are discussed in chapter 3.1.5. on fossil methane, apply equally to power-to-methane. This includes engine efficiency, fuel storage, air pollutant emissions and necessary vehicle adaptations. For the reason that long-haul HGVs require a higher vehicle range, gas-powered tractor trailers need to store their onboard fuel in liquefied form (LNG), which has further efficiency implications. As reported by Shell, 8% of the LNG produced is needed as energy input for the liquefaction process.[179]

The hydrocarbon-based gaseous fuel is produced through methanation. The process requires hydrogen from renewable electricity and CO_2 from DAC as feedstock in order to generate methane and water as a by-product.[180] Similar to hydrogen and PtL, a high utilisation rate is necessary to operate the production

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[xxi] Synthetic electrofuels do not contain impurities such as heavy metals and sulphur, but the exhaust does contain particulates, NOx and carbon monoxide (CO). The amounts of particulates are likely to be lower than fossil-derived fuels (due to the absence of impurities) while studies have shown that NOx emissions are similar or lower.

facilities cost-effectively. As for PtL, 4,000 full-load hours and temporary hydrogen storage are assumed for the cost analysis.[181]

For the PtM pathway, the chosen engine technology is a dual-fuel CI HPDI gas engine for which the same fuel efficiency as conventional diesel engines was assumed (2.96 kWh/km in 2020 and 2.33 kWh/km in 2030). This is based on literature and manufacturer statements.[182] No additional energy losses due to boil-off or venting are considered. In reality, an estimated 10% of the vehicle's total fuel consumption is due to diesel fuel which is needed to ignite the fuel-air mix. For reasons of simplification, the emissions modelling and cost analysis assume that these vehicles run on synthetic methane only.

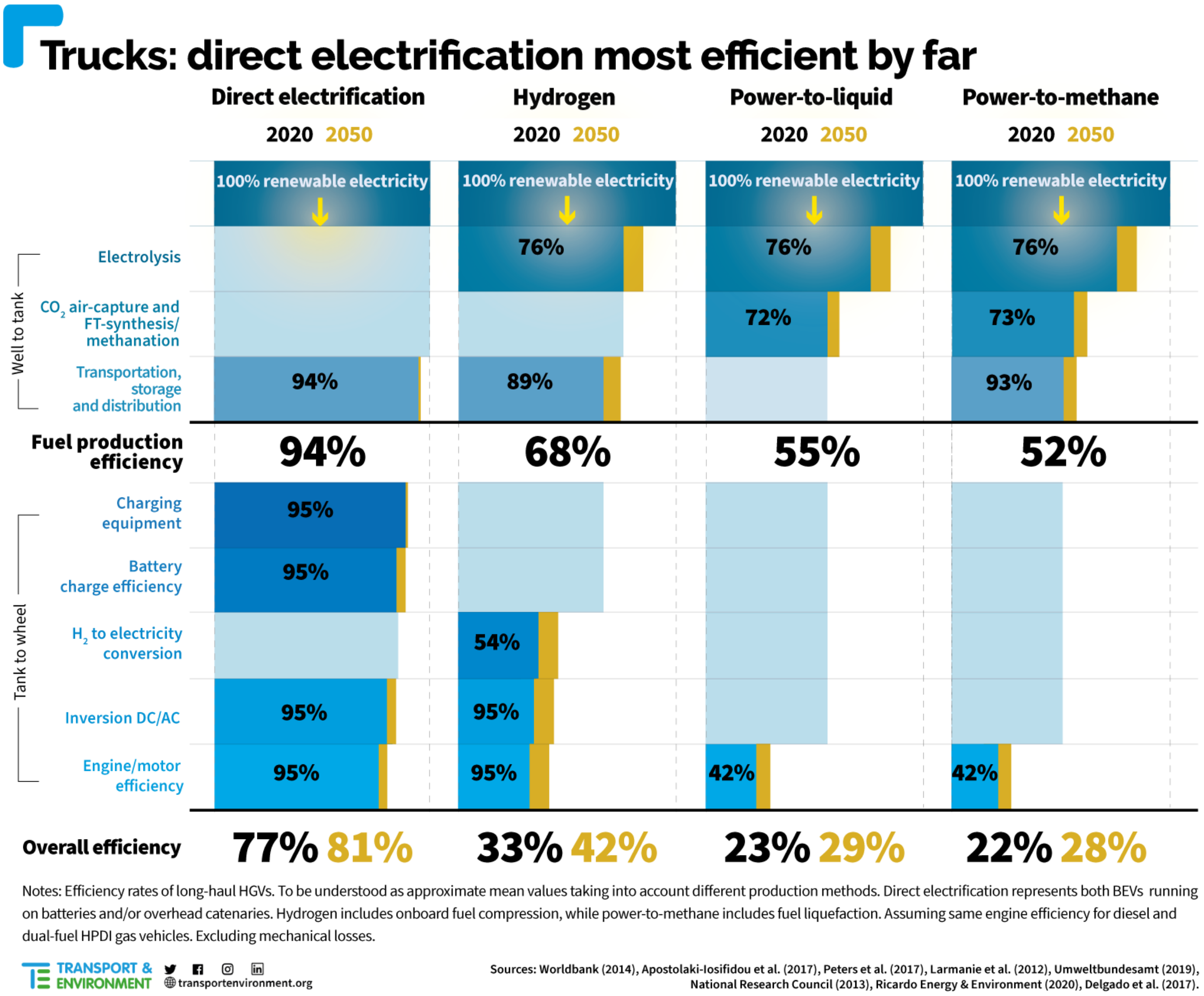
ICEVs_PtM would require the deployment of additional LNG refuelling infrastructure. As of today, there are 18 operating LNG refuelling stations in the UK whose individual refuelling capacity ranges between 5,000 and 21,000 kg_{LNG}.[183] The exemplary LNG refuelling station used for the cost analysis has a capacity of 17,000 kg_{LNG}.

It should be mentioned that opting for the PtM pathway would carry the significant risk of a potential fossil fuel infrastructure lock-in. Once vehicle manufacturers, hauliers and infrastructure operators would make large-scale investments in the technology, they would have an inherent interest to prevent them from becoming stranded assets. In the scenario where not enough sustainably sourced biomethane and power-to-methane was available or it to be too expensive, the likelihood would increase that the involved stakeholders revert to fossil methane in order to fill the supply gap.

4. Additional renewable electricity demand

The different pathways are subject to different conversion efficiency losses and therefore need varying amounts of renewable electricity, either through direct electrification or as feedstock for the production of electricity-based fuels. Figure 13 below shows the average conversion efficiency rates for the different pathways based on todays and the maximum technical potential in 2050.[xxii] Direct electrification will remain, today and in the future, at least twice as efficient as hydrogen and around three times as efficient as internal combustion engines running on synthetic liquid or gaseous electrofuels.

[xxii] The conversion efficiency rates in Figure 13 serve illustrative purposes and are to be understood as mean values taking into account different production methods. The calculation of electricity and fuel costs in the cost analysis (see chapter 5) are based on the exact fuel production efficiencies of the Agora PtG/PtL calculator (well-to-tank) and the vehicle fuel consumption values (tank-to-wheel).



Trucks: direct electrification most efficient by far

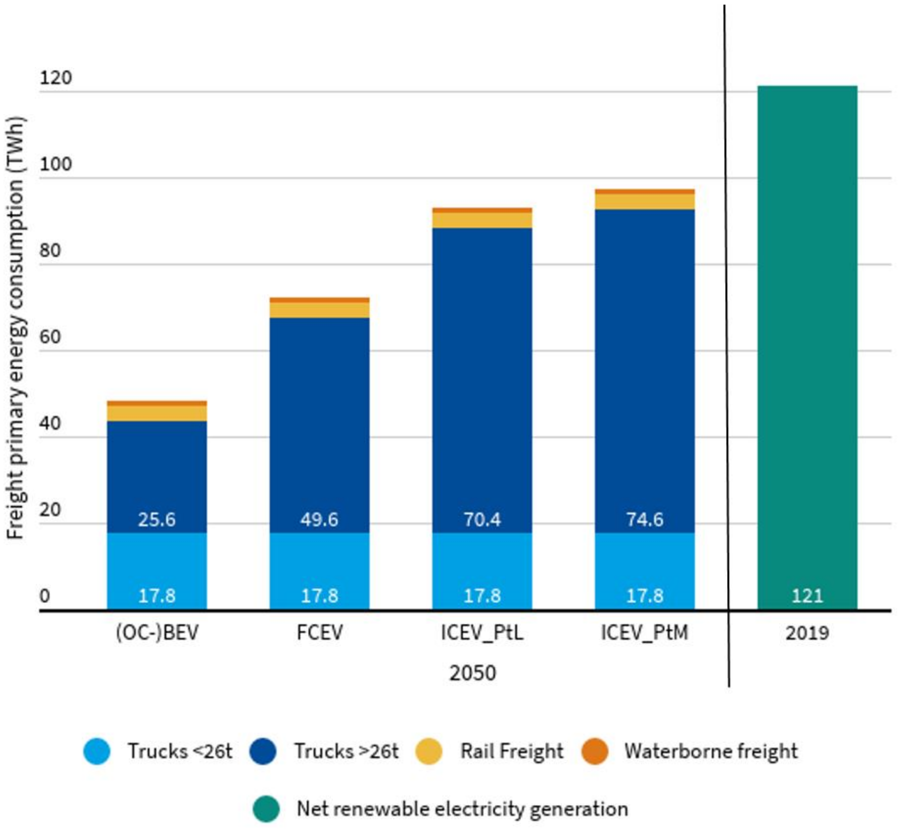
Notes: Efficiency rates of long-haul HGVs. To be understood as approximate mean values taking into account different production methods. Direct electrification represents both BEVs running on batteries and/or overhead catenaries. Hydrogen includes onboard fuel compression, while power-to-methane includes fuel liquefaction. Assuming same engine efficiency for diesel and dual-fuel HPDI gas vehicles. Excluding mechanical losses.

Sources: Worldbank (2014), Apostolaki-Iosifidou et al. (2017), Peters et al. (2017), Larmanie et al. (2012), Umweltbundesamt (2019), National Research Council (2013), Ricardo Energy & Environment (2020), Delgado et al. (2017).

Figure 13: Conversion efficiencies of different powertrain technologies

This has an impact on the amount of renewable energy needed for the different pathways. Figure 14 illustrates the additional renewable electricity demand and compares it to the 2019 net renewable electricity generation in the UK. Battery electrification for HGVs up to 26 tonnes GVW is assumed across all pathways. The differences in total primary renewable energy consumption are thus due to HGVs above 26 tonnes. In 2050, the direct electrification pathway would require an equivalent of 40%, the hydrogen pathway of 60% and the two hydrocarbon pathways of 77% and 80% compared to the 2019 net renewable electricity generation in the UK.[xxiii]

[xxiii] In this respect, it is again noted that the demand projections do not take into account possible interactions between modes due to changes in freight demand and transport costs, (i.e. *ceteris paribus*). Any change in freight demand due to price elasticity from changing transport and fuel costs is not fed back into the emissions modelling.



Notes: Battery electrification for trucks below 26 tonnes is assumed across all pathways

Sources: T&E calculations and BEIS (2020).

Figure 14: 2050 primary energy consumption compared to the 2019 net renewable electricity generation in the UK

In the context of the wider energy transition and the imperative to fully decarbonise all economic sectors including the power, industry and heating sectors, substantial additional renewable electricity capacity will be needed in the UK. Clean electricity should therefore be used as efficiently as possible. Because the decarbonisation of the aviation and shipping sector as well as other hard-to-abate sectors such as industry will rely on electricity-based fuels and renewable hydrogen in particular, direct electrification needs to take precedence in road transport.

5. Cost analysis for long-haul trucks

The costs due to the renewable electricity demand are only one of the cost components which need to be considered. The system costs describe the total capital and operating costs for each vehicle, taking into account its purchase, fuel consumption and its refuelling or recharging infrastructure needs. The user costs, or total cost of ownership (TCO), describe the full purchase, ownership and operating costs including all taxes, levies, road charges and subsidies. Labour costs are not considered as they do not differ no matter which technology is chosen.

5.1. System costs

Unlike a TCO, the system costs refer to economic costs that need to be borne to a different degree by the manufacturers, operators, consumers and the public sector. It excludes all taxes, levies and road charges except for electricity grid connection and network and distribution costs in order to allow for an undistorted assessment of the real costs and a fair comparison between the different technologies.

5.1.1. Vehicle costs

The vehicle costs are mostly based on Kühnel et al. and can be found in Annex II.[184,xxiv] All vehicles across the pathways share the same characteristics required to meet the typical application profile of a long-haul tractor trailer under type-approval in the UK (see Table 4). It has a GVW of 44 tonnes, a vehicle curb weight of 14.4 tonnes and a resulting maximum payload of 29.6 tonnes. The majority of articulated HGVs registered in the UK have a GVW of 44 tonnes and, thus, meet the 6x2 axle type and road friendly suspension requirements.[185] The long-haul duty cycle involves multi-day intercity travel with maximum daily trip lengths of around 800 km if the vehicle is operated by one driver. The vehicle costs are kept constant after 2030 and until 2050. They take into account a vehicle use period of five years and the remaining residual value of the vehicle. The average annual mileage is set at 120,000 km based on estimates by the European Commission.[186] This translates to an average daily mileage of 480 km based on 250 operating days per year.

Kühnel et al. undertook a bottom-up cost estimation for the different vehicle components and included a markup factor of 1.4 to determine the net retail price after manufacturing, assembly and distribution costs as well as the profit margin. The total net retail price (excluding vehicle taxes, VAT, insurance and financing costs) include the applicable costs due to the glider, conventional powertrain (internal combustion engine, exhaust aftertreatment system and diesel tank), electric powertrain (electric motor, inverter and gearbox), fuel cell system (Proton Exchange Membrane (PEM) technology with a rated power of output of 180 kW), hydrogen fuel tank (compression at 700 bar), battery pack and the pantograph. Maintenance & repair (M&R) costs refer to costs due to general vehicle servicing, the urea solution for the exhaust aftertreatment system and the pantograph over the first use period. The net retail price for the BEV also takes into account a weight penalty due to the additional vehicle weight and lost payload before 2030. Since a proportion of vehicle trips are carried out not fully loaded, it is presumed that 50% of vehicles would be constrained by weight limitations in line with Hall et al.[187] Hill et al. estimated the share of vkm that are constrained by weight limitations to be between 10% and 19.5% for long-haul operations.[188] A time penalty is not considered as the BEV is charged in alignment with driving times and rest periods without affecting operations.

The battery pack costs are based on Bloomberg NEF's 2019 forecast and include the same mark-up factor of 1.4 as the one for the vehicle costs to determine the pack's retail price after manufacturing and distribution costs. These estimates are comparable to other battery pack cost curve projections.[189] The battery pack density values are the low assumptions on the potential for future technological improvement based on Ricardo Energy & Environment.[190] A sensitivity analysis was undertaken to account for a scenario where battery pack costs are declining more rapidly than currently projected.

The estimated vehicle costs are based on a hypothetical scenario where the manufacturing capacities and production lines are well developed and those vehicles are mass-produced on a larger scale. In this context, the 2020 values should be viewed with caution since large-scale production has not yet taken place. This is particularly the case for technology which is currently not produced in larger units for neither the light-duty nor heavy-duty vehicle market. For example, the estimated component costs for the fuel cell and hydrogen tank systems imply an annual production of 1,000 units in 2020, 10,000 units in 2025 and 50,000 units in 2030 based on the U.S. Department of Energy and Moultak et al.[191,192]

[xxiv] The cost assumptions made by Kühnel at el. are based on the German cost level. Since the price level and purchase power in Germany and the UK are broadly similar, the costs should be comparable.

Parameters	ICEV_diesel	BEV	OC-BEV	FCEV	ICEV_PtL	ICEV_PtM
Powertrain technology	Diesel engine	Electric motor			Diesel engine	Dual-fuel CI HPDI engine
Energy storage	Diesel tank	Battery		compressed H_2 fuel tank - battery	Diesel tank	LNG tank - diesel tank
Fuel tank and nominal battery size in 2030	570 L	1,022 kWh	256 kWh	47 kg_{H2} - 70 kWh	570 L	205 kg_{LNG} - 170 L
Maximum range without refuelling / recharging in 2030	> 1,900 km	800 km	> 800 km - 200 km on battery	800 km[xxv]	> 1,900 km	920 km

Table 4: Long-haul tractor trailer vehicle specifications in 2030

5.1.2. Fuel costs

The Agora PtG/PtL calculator was used to calculate the levelised cost of electricity (LCOE) and the cost of electricity-based fuels produced from it.[193] It should be noted that all pathways are based on renewable electricity. This has been a deliberate choice in order to provide for a level playing field and compare the technologies which can ensure zero well-to-wheel GHG emissions (though not lifecycle GHG emissions). In terms of the lifecycle climate performance, emissions incurred from the construction and eventual dismantling of electricity and fuel production facilities are not taken into account.[194] Likewise, any potential time-related constraints to their scale-up are disregarded and it is assumed that the additional final energy demand from HGVs is met with an increasing generation and production capacity without any limitations. The detailed fuel cost components can be found in Annex II.

The electricity generation and fuel production facilities are based on offshore wind in the North Sea with connection to the UKs electricity grid and domestic fuel production plants (if applicable). The MENA region is considered to be a particularly favourable location to produce renewable hydrogen and synthetic electrofuels more cheaply due to lower renewable electricity costs. A sensitivity analysis was therefore undertaken based on solar PV in North Africa for electricity-based fuels.

The calculated costs are based on the reference scenario of the Agora PtG/PtL calculator. The chosen weighted average cost of capital (WACC) is 6% and the method of CO_2-extraction is DAC.[195] Offshore wind in the North Sea was set at a load factor of 4,000 full-load hours per year. High-temperature electrolysis as well as FT-synthesis and methanation operate at the same load factor.[196,xxvi] For the sensitivity analysis, solar PV

[xxv] Hydrogen trucks can be equipped with a larger tank to reach ranges of around 1,200 km. A larger hydrogen fuel tank would also entail higher component costs. It was therefore decided to align the assumed range among the zero-emission vehicle options to allow for comparability.

[xxvi] High-temperature proton-conducting solid oxide electrolysis cells (SOEC), which show the lowest level of conversion losses, are the least developed electrolysis technology and are currently at a pre-commercial stage. The technology was chosen for the cost analysis to account for the maximum technical potential.

in North Africa was set at 2,344 full-load hours as it is the case for electrolysis.[xxvii] The FT-synthesis and methanation process were set at 4,000 full-load hours and, thus, rely on temporary hydrogen storage.

Grid connection fees are included in the LCOE for the direct electrification pathway. In addition, it includes UK-specific network and operating costs as the equivalent to fuel transportation and distribution costs based on cost estimates by the Office of Gas and Electricity Markets (Ofgem).[197] If the electricity-based fuels are produced overseas, they take into account costs due to liquefaction (if applicable), subsequent transport via tanker vessel from North Africa (Algiers) to the Port of Milford Haven (the UK's largest entry port for energy and liquid bulk products including LNG) and distribution to the refuelling station via insulated cryogenic tanker trucks (hydrogen) or conventional tanker trucks (synthetic diesel and LNG).[198]

Fuel liquefaction, transportation and distribution costs are based on the U.S. Department of Energy, Hydrogen Council, Pfennig et al., Mottschall et al., Agora Verkehrswende et al., Fasihi et al. and Bünger et al.[199,200,201,202,203,204] The fossil diesel pathway includes the nine-year average diesel fuel pump price between 2011 and 2020 amounting to £-pence 49.19/L (excluding fuel duty and VAT).[205] This price is kept constant until 2050.

5.1.3. Infrastructure costs

The estimated infrastructure costs are also based on Kühnel et al. They take into account the size and power of the refuelling and charging stations, a high utilisation rate, service life, capital expenditure, operational expenses and the number of supplied vehicles per refuelling or recharging station. A sensitivity analysis was undertaken for the OC-BEV based on a low utilisation rate of the overhead catenary infrastructure. It should be noted that refuelling and recharging cost estimations are to an extent speculative as the technologies are not yet (fully) commercialised, let alone scaled up on the market. The costs for both the recharging and refuelling stations follow similar cost reduction curves until 2030 and are kept constant afterwards. The costs for LNG refuelling stations are assumed to not decrease further because the technology is already commercialised and widely deployed. The detailed cost components can be found in Annex II.

The fossil diesel and the PtL pathways can use the already established refuelling infrastructure. It is therefore assumed that the capital costs of these refuelling stations are already written off, the operational expenses are insignificant and the infrastructure does not need to be replaced after its service life ends.

5.1.4. Results

The lifetime system costs per new vehicle are shown in Figure 15 and include the fossil diesel pathway to allow for comparison. As mentioned, the system cost approach permits a calculation of the true techno-economic costs of the different pathways and should not be confused with a TCO whose additional cost components will be presented afterwards.

[xxvii] It is possible to combine solar PV and wind power instead of solar PV alone, which would then allow for a higher load factor of the electrolyser. However, LCOE from wind is higher than from solar PV and a combination of both would result in higher levelised fuel costs than from solar PV alone according to the Agora PtG/PtL calculator.

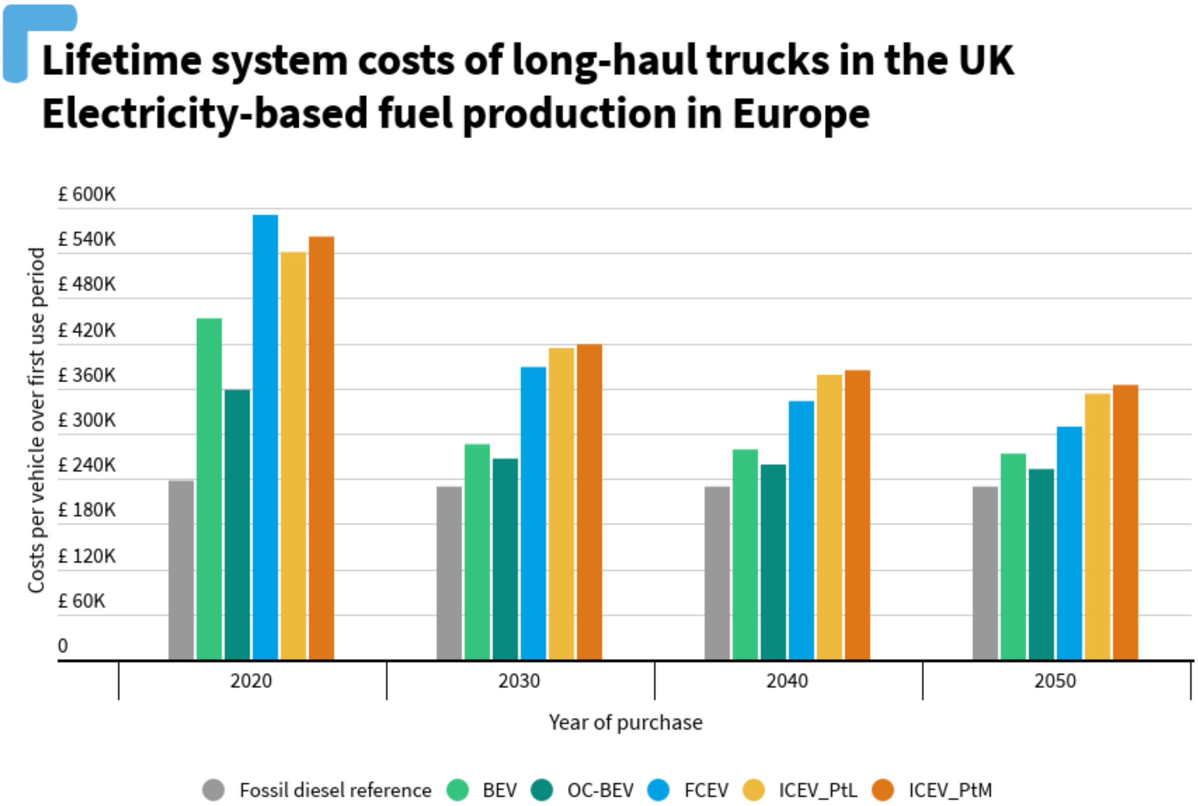

Lifetime system costs of long-haul trucks in the UK
Electricity-based fuel production in Europe

Figure 15: Lifetime system costs - base case with electricity-based fuel production in Europe

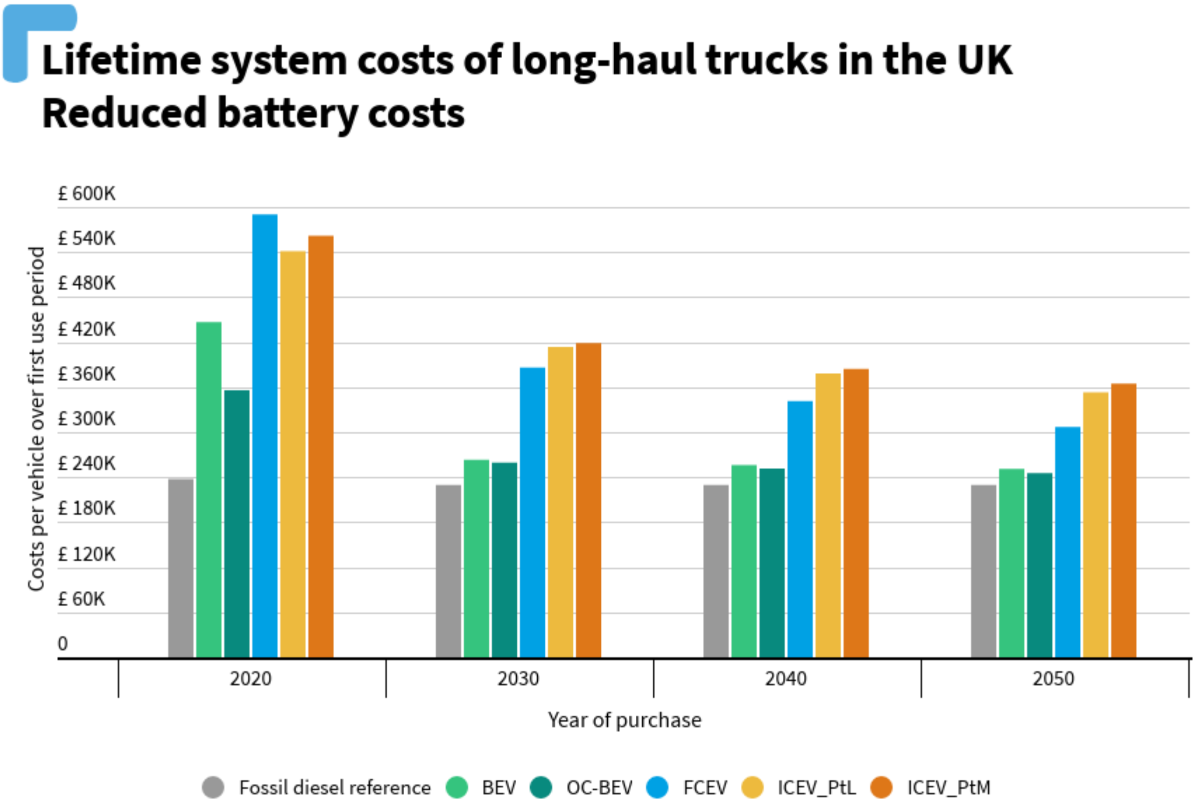
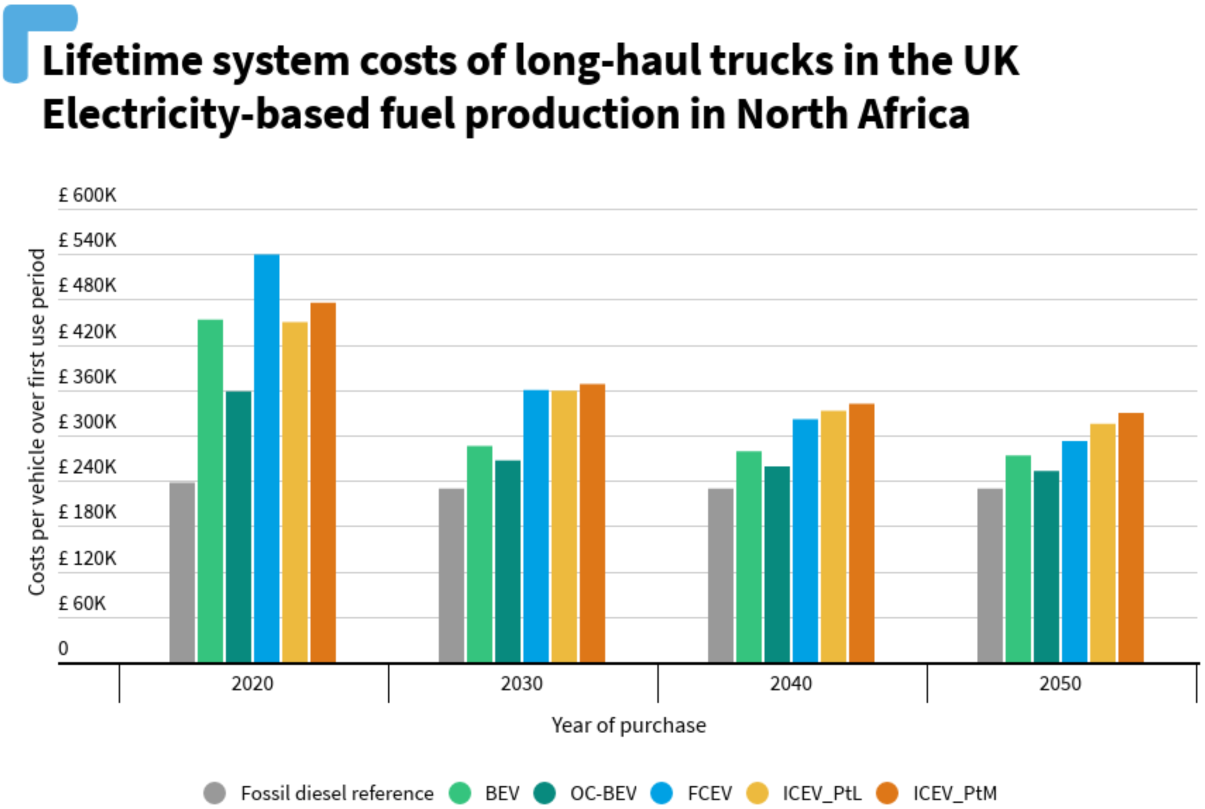
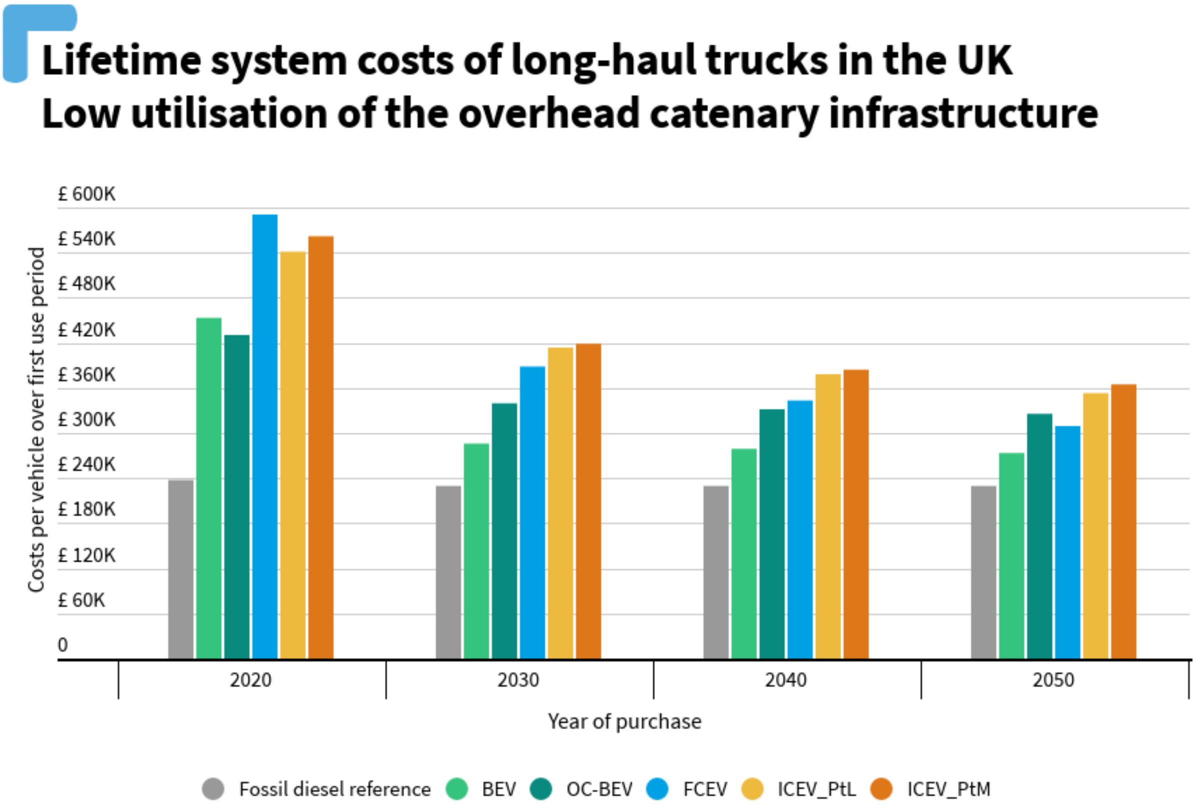

Lifetime system costs of long-haul trucks in the UK
Reduced battery costs

Figure 16: Lifetime system costs - sensitivity analysis with reduced battery costs



Lifetime system costs of long-haul trucks in the UK
Electricity-based fuel production in North Africa

Figure 17: Lifetime system costs - sensitivity analysis with electricity-based fuel production in North Africa



Lifetime system costs of long-haul trucks in the UK
Low utilisation of the overhead catenary infrastructure

Figure 18: Lifetime system costs - sensitivity analysis with low utilisation of the overhead catenary infrastructure

The results indicate that BEVs and OC-BEVs will likely represent the most cost-effective option amongst all pathways which can achieve zero well-to-wheel emissions by mid-century. A faster cost reduction curve of batteries would have a big impact on the total system costs. BEVs and OC-BEVs will likely also be cheaper to own and operate than FCEVs running on renewable hydrogen or ICEVs running on synthetic diesel or methane if those electricity-based fuels are produced overseas more cheaply and shipped to the UK. Lower infrastructure utilisation rates, notably in the case of overhead catenaries, can have a notable effect on the total system costs.

5.2. Total cost of ownership

The total cost of ownership (TCO) comprises the system costs and all taxes and levies on vehicle purchase, operation and fuel as well as road charges. In this sense, the TCO describes the total costs for the operator to own and operate the vehicle.

5.2.1. Taxes, levies, charges and subsidies

As explained above, the system costs already include grid connection fees for the renewable electricity generation facilities as well as costs for transport and distribution infrastructure for both electricity and fuels. In addition to this, the TCO includes all taxes and levies (excluding VAT) on the purchase and use of the vehicle and the final fuel end product. This means that electricity-based fuels are taxed only once as their final product. The electricity required as input for the production of those fuels is assumed to be fully exempt from taxes and levies.

The taxes on vehicle purchase and operation include the one-time registration charge and the annual Vehicle Excise duty (VED) if the HGV is taxed as a 'goods vehicle'.[206,207] The HGV road user levy, a time-based road charging system, amounts to £ 900 p.a. for Euro VI vehicles.[208] The current temporary one-year suspension is assumed to end by mid-2021 as planned.

For the fossil diesel as well as the power-to-liquid pathway, the diesel fuel duty rate of £-pence 57.90/L is included and kept constant over time without inflation adjustment.[209] The electricity pathway includes the so-called environmental and social obligation costs including the Climate Change Levy based on Ofgem (£-pence 3.82/kWh).[210] Hydrogen used in a fuel cell is currently exempt from fuel duty in the UK.[211] This subsidy is maintained. For the power-to-methane pathway, the fuel duty rate for natural gas used as fuel in vehicles of £-pence 24.70/kg is added.[212]

Resulting in a final renewable electricity price for the end user of £-pence 19.67/kWh in 2020, this is slightly higher than the current domestic grid electricity price for large consumers in the UK which amounted to £-pence 17.79/kWh in 2019.[213,xxviii] The final renewable hydrogen price for the end user is between £ 5.92/kg and £ 7.17/kg in 2020 which compares to an estimated final fossil-derived hydrogen price of £ 2.04/kg (without CCS, i.e. 'grey') and £ 4.57/kg (with CCS, i.e. 'blue') in the UK today.[214,xxix]

The UK' plug-in grant scheme covers up to 20% of the vehicle purchase price with a maximum grant rate of £ 8,000 for vehicles with at least 50% less CO_2 emissions compared to the equivalent Euro VI vehicle. This reduces the vehicle purchase costs of the BEV, OC-BEV and FCEV by the full amount of £ 8,000 throughout the 2020s.

5.2.2. Results

The lifetime TCO per new vehicle is shown in Figure 16 and includes the fossil diesel pathway to allow for comparison. It takes into account a first use period of five years and the remaining residual value.

[xxviii] The domestic electricity price for large consumers refers to an annual consumption between 5,000 - 15,000 kWh per year as of the second half of 2019 and includes environmental taxes and levies except for VAT.

[xxix] The fossil-derived hydrogen production costs by the IEA are for Europe and include additional liquefaction and distribution costs as it is assumed that it is produced centralised for CO_2 storage reasons.

Total cost of ownership of long-haul trucks in the UK
Electricity-based fuel production in Europe

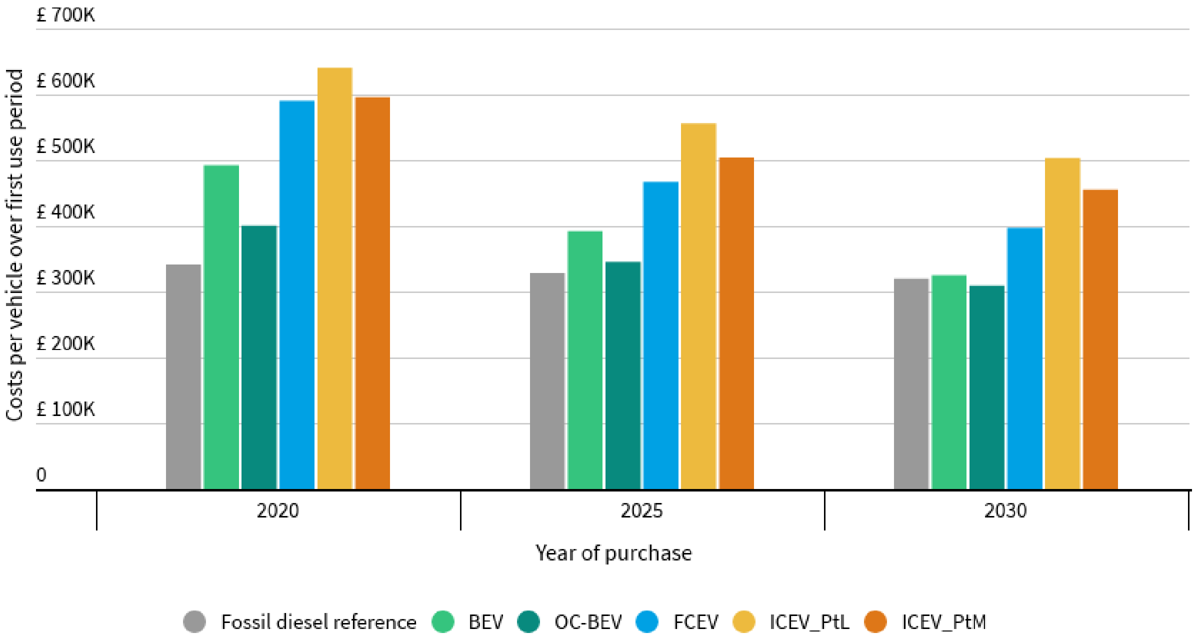


Figure 19: TCO - base case with electricity-based fuel production in Europe

TCO per km of long-haul trucks in the UK in 2030
Electricity-based fuel production in Europe

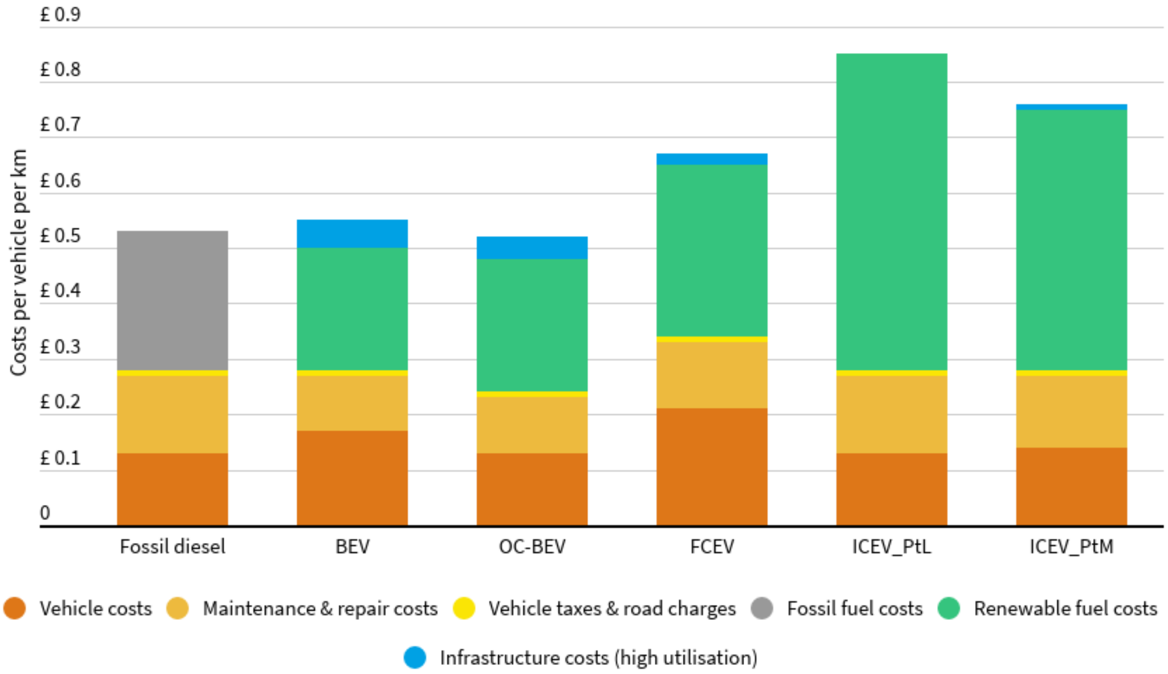
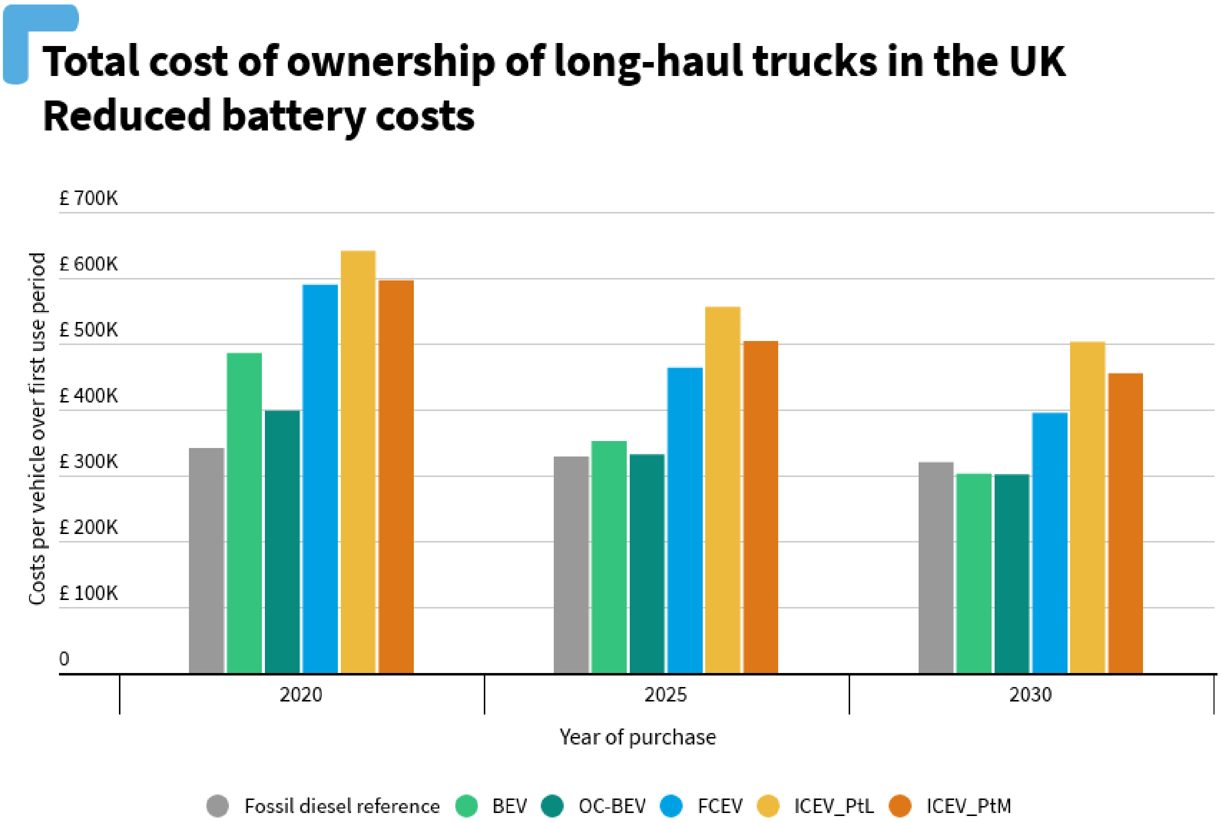
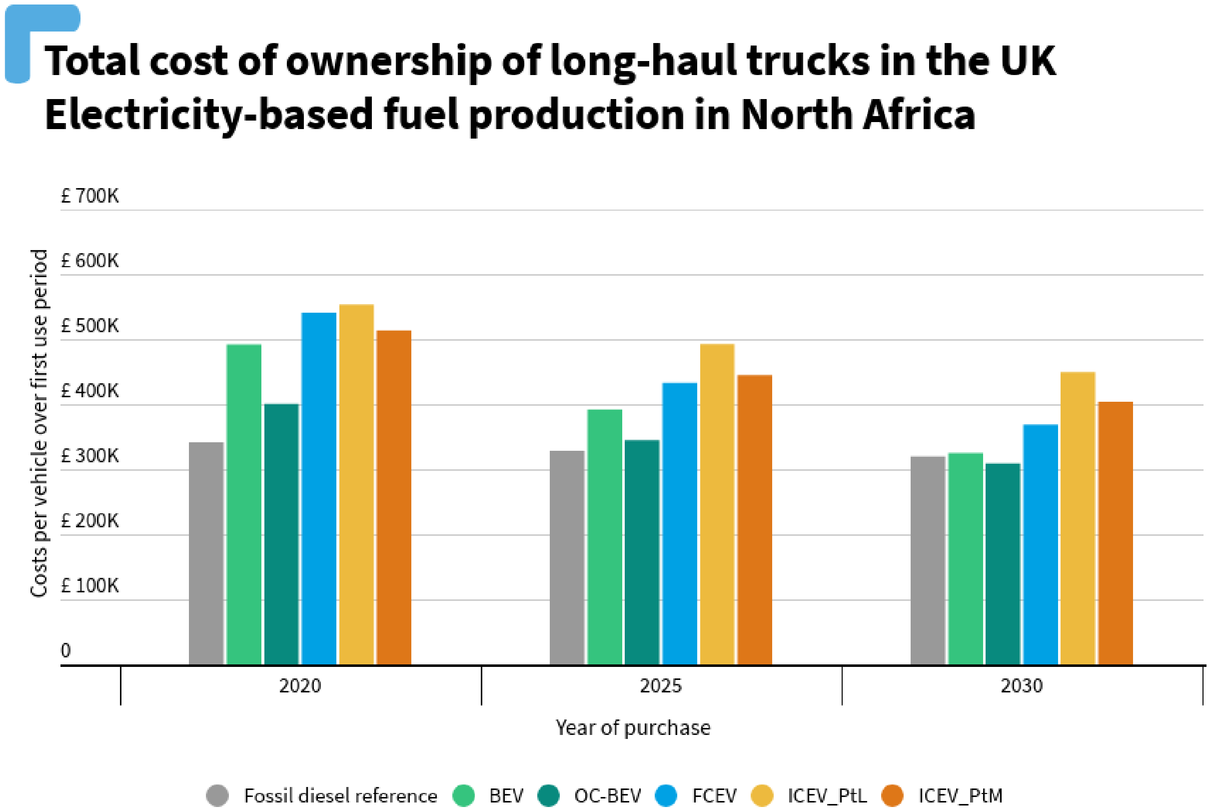


Figure 20: TCO per km in 2030 - base case with electricity-based fuel production in Europe



Total cost of ownership of long-haul trucks in the UK Reduced battery costs

Figure 21: TCO - sensitivity analysis with reduced battery costs



Total cost of ownership of long-haul trucks in the UK Electricity-based fuel production in North Africa

Figure 22: TCO - sensitivity analysis with electricity-based fuel production in North Africa

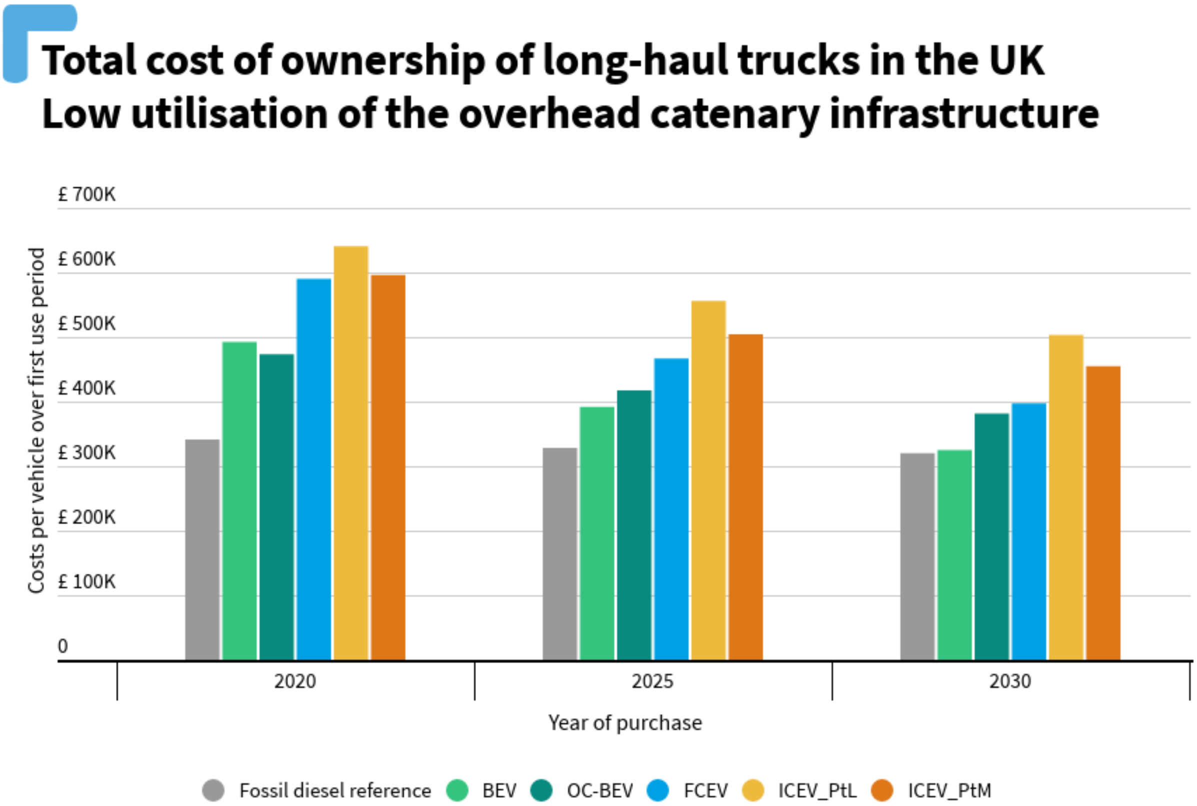


Figure 23: TCO - sensitivity analysis with low utilisation of the overhead catenary infrastructure

Also when accounting for all taxes, levies, road charges and current subsidies, BEVs and OC-BEVs represent the most cost-effective option amongst the pathways. Without any additional subsidies, OC-BEVs could reach price parity with the fossil diesel pathway in the late 2020s, BEVs in the late 2030s and FCEVs in the mid 2040s. The electric powertrain options will likely also then be cheaper to own and operate compared to FCEVs and ICEVs running on electricity-based fuels if those are produced in North Africa and shipped to the UK. It is also worth noting that the above TCO already includes a tax exemption for hydrogen but no subsidies for electricity used in transport.

6. Conclusion: the optimal pathway

Battery electric trucks and those using an overhead catenary infrastructure are likely to be the most cost-effective pathway to replace the current fossil diesel-powered fleet and achieve zero inland freight emissions in the UK by 2050. A modal shift away from the road and towards rail is to a limited extent possible. However, this limited potential should not be overestimated given that, in the model's UP scenario, rail freight capacities already increase by 24%. In the medium-term, efficiency measures can contribute to bringing down inland freight emissions in the UK. But they are not even sufficient to reach the 2030 target, let alone fully decarbonise the sector by 2050. A powertrain transition towards zero-emission vehicles for urban, regional delivery and long-haul freight is essential to meet the climate targets at the least societal cost.

7. Policy recommendations

In order to achieve the UK's goal of net zero emissions by 2050, inland freight transport in the UK needs to be zero emission by 2050. To achieve this, new regulations will be needed and complemented by investment in infrastructure and taxation reform to deliver the transformation. This will require action at the national level, particularly by the Department for Transport and Treasury, at the local level through mandating zero-emission deliveries in urban areas and at the business level to supply and use the new technology.

In its 2020 Progress Report to Parliament, the CCC called on the UK government to 'set out and implement a strategy to transition to zero-carbon freight, including stronger purchase incentives, infrastructure plans and clean air zones.[215] The Transport Decarbonisation Plan should establish the long term goal of zero emissions in freight by 2050 (not net zero) and concrete policy proposals that will set the UK on a path to achieve this challenging but essential commitment:

The idiom is you eat an elephant one bite at a time - and this must be the approach for decarbonising freight. There are 3 quite separate challenges relating to:

1. Urban and last mile delivery
2. Regional delivery
3. Long-haul freight.

This study shows that modal shift, such as increasing the share of last mile deliveries using cargo bikes and long-haul distribution using rail can play a small but valuable role in decarbonising freight and should be actively encouraged. But it is changing from fossil diesel to battery electric vans as well as urban and regional delivery trucks that will deliver most of the emission reductions and are the first bites. This can be achieved without imposing excessive additional demands on electricity generation so long as smart (offpeak) charging is the norm.

For long-haul freight the picture is more opaque. Battery electric trucks charged through high-power charging points, catenary systems and fuel cell electric trucks running on renewable hydrogen are all credible options at the present time. For long-haul freight further work and trials are needed along with discussions with international trading partners to decide on the ultimate solution(s). However, the uncertainty of how to decarbonise long-haul freight should not delay progress on urban and regional delivery freight where it is clear that battery electric trucks will dominate and progress can be made quickly.

7.1. Taxation reform

Road freight transport is a business and for a rapid shift to zero emission deliveries there must be both strong regulation and a business case to transition. A variety of tax reforms can help to improve the economics of zero-emission trucks and help create strong demand for new technologies.

Electricity taxation

There are currently no reduced tax rates foreseen for electricity used in road freight transport. An exemption from the Climate Change Levy (£-pence 0.81/kWh since April 2020) is currently granted to the transportation of passengers and goods by train.[216] This provision should be extended to the transportation of goods by HGVs directly using electricity, i.e. BEVs and OC-BEVs. This would help to level the playing field between battery electric and hydrogen trucks as the latter already benefits from a full fuel duty exemption.

Natural gas fuel duty

The UK is currently applying an extremely low fuel duty rate to natural gas used in transport (£-pence 24.70/kg) regardless whether it is fossil-derived or biomethane. A high proportion of the gas supplied to the transport sector today is renewable and there is no reason to offer a duty break to fossil gas. The Treasury should adjust the reduced rate so this only applies to biomethane which is sourced from advanced waste- and residue-based feedstocks and which qualifies for the Renewable Transport Fuel Obligation (RTFO). Fossil gas should be taxed on an energy content basis at the same level as diesel. Biomethane can play a niche role in decarbonising freight but is very unlikely to be able to scale sustainably to play a major role.

Diesel fuel duty

The diesel fuel duty rate has been frozen since 2011. As a minimum, it is essential to introduce an annual indexation of the fuel duty rate in line with the Consumer Prices Index (CPI). The historical average inflation rate since 1988 has been around 2.5% annually.[217] Additionally, a reintroduction of the fuel duty escalator (raising duty rates at a rate faster than inflation) would progressively equalise diesel fuel duty at 2010 levels and be a powerful stimulus to accelerate the shift to zero-emission trucks. The currently low oil prices are a good opportunity to make progress in this regard.

7.2. Supply of zero-emission trucks

National sales phase-out of ICE trucks

The lack of supply of zero-emission trucks is one of the key barriers holding back the market. To address this the UK should adopt a sales phase-out for new ICEVs with a GVW below 26 tonnes for 2035 at the latest and above 26 tonnes before 2040. The industry is already moving into this direction: Daimler, the world's biggest truck manufacturer, has already announced to end the development of ICEVs and that from 2039 all trucks sold in the triad markets of Europe, Japan and North America will be ZEVs, i.e. battery electric and hydrogen.[218] Such a phase-out date can be incorporated into the CO_2 standards or a ZEV target (see below).

CO_2 standards for new HDVs and ZEV sales target

The EU has recently adopted its first-ever CO_2 emission performance standards for trucks. To address the supply gap and ensure that today's available fuel efficiency technology reaches the UK market, the UK government should urgently transpose the European CO_2 emission performance standards into national law as it is currently already planning to do so.[219]

Since the current heavy-duty average fleet reduction target for 2030 is insufficient to meet the UK's climate targets, the UK should increase regulatory ambition as soon as possible.[220] One of the most effective and least cumbersome ways to do that would be the introduction of a mandatory ZEV sales target for 2025 and the following years. This would oblige manufacturers to sell a certain share of ZEVs as part of their total fleet sales in the UK. The targets could vary depending on the vehicle category and weight class. California's Advanced Clean Trucks Regulation set a binding sales mandate from 2024 onwards including a 40% zero-emission sales target for class 7 and 8 tractors (GVW above 12 tonnes) by 2032.[221] Such a ZEV target can provide the legal mechanism through which to deliver the sales phase-out for ICEVs with a GVW below 26 tonnes for 2035 and above 26 tonnes before 2040.

In addition to measures to drive the shift to zero-emission trucks, accelerated progress is also needed to reduce the CO_2 emissions from diesel trucks where there remains considerable potential for efficiency improvements. Specifically:

- The reduction target for 2030 should be increased beyond the current 30%. A noticeable part of the 2030 fleet reduction target will be met by the increasing deployment of ZEVs, a trend which will continue to intensify in the coming years.
- The CO_2 standards and VECTO need to be extended to cover the currently unregulated vehicle types (trailers and buses) and vehicle groups (other than 4, 5, 9 and 10) to the largest extent which is practically implementable. The UK should cooperate closely with the EU in this regard to advance the further development of VECTO. By the end of 2022, the European Commission will consider extending the CO_2 standards to the currently unregulated vehicle types (including trailers and buses).

Vehicle weights and dimensions

The two-tonne additional maximum weight allowance for ZEVs, which was introduced by the European CO_2 standards as an amendment to the Weights and Dimensions Directive, needs to be transposed into UK national law. Although the UK will cease to be bound by EU law after 2020, it is strongly recommended to amend the The Road Vehicles (Authorised Weight) and (Construction and Use) Regulation in order to compensate for the currently still higher vehicle weight of battery electric- and hydrogen-powered vehicles compared to ICEVs.[222]

The same applies to the recent EU Decision setting special rules regarding maximum lengths for cabs delivering improved aerodynamic performance.[223] The Decision amends the Weights and Dimensions Directive to allow the exceedance of the maximum vehicle length if the vehicle cab delivers improved aerodynamic performance, energy efficiency and safety performance. This should be transposed into national law as well.

7.3. Demand for zero-emission trucks

Purchase incentives

Today's limited availability and higher upfront purchase costs are a significant barrier for hauliers investing in ZEVs despite lower operating costs. In order to incentivise the purchase of ZEVs and accelerate the market uptake, meaningful purchase subsidies will initially be needed. Purchase grants are expensive for the public finances so need to be applied only during the early market phase and be limited to ZEVs. Grants should not be made available for gas-powered trucks as biomethane supply cannot scale to supply a significant share of trucks.

The UK has extended the plug-in grant scheme to large vans and trucks covering up to 20% of the vehicle purchase price with a maximum grant rate of £ 8,000 for vehicles with at least 50% less CO_2 emissions compared to the equivalent Euro VI vehicle. This purchase subsidy should be reformed and limited to ZEVs. In its 2020 Progress Report, the CCC recommended strengthening purchase incentives for HGVs and higher rates are currently available in Germany and California.[224] In Germany operators can receive grants of up to € 12,000 (GVW up to 12 tonnes) and € 40,000 (above 12 tonnes) per vehicle, whereby a maximum 40% of the additional vehicle investment costs are covered and the maximum funding a single company can receive through the scheme is capped at € 500,000.[225] Germany is planning to extend its purchase subsidy scheme in the near future.[226] The Federal State of Baden-Württemberg provides a maximum grant of € 100,000 covering a maximum 50% of the extra vehicle investment costs.[227] California is providing purchase funding rates going as high as $ 150,000 for HGVs above 15 tonnes GVW.[228]

Road charging

Currently, HGVs operating in the UK only have to pay a time-based road charge for the use of the road network. A time-based system fails to deliver the necessary steering effect and fails to encourage either efficient trips or a shift to zero-emission vehicles. It also runs contrary to the user- and polluter-pays principle. With a view to internalise a greater share of externalities caused by trucks and offset the expected future fuel duty revenue decline, the UK government should introduce a distance-based road charging scheme for all ICE trucks with a GVW above 3.5 tonnes circulating on UK roads while exempting ZEVs. The scheme could subsequently be extended to vans. Such an approach in combination with an indexation of the diesel fuel duty rate will drive logistics efficiency and the shift towards zero-emission technology.

Fuel duty indexation and distance-based road charging: impact on the TCO

Maintaining the current plug-in grant and combining it with a diesel fuel duty indexation and the introduction of a distance-based road charging scheme for ICE trucks will accelerate the transition and bring forward price parity with fossil diesel.

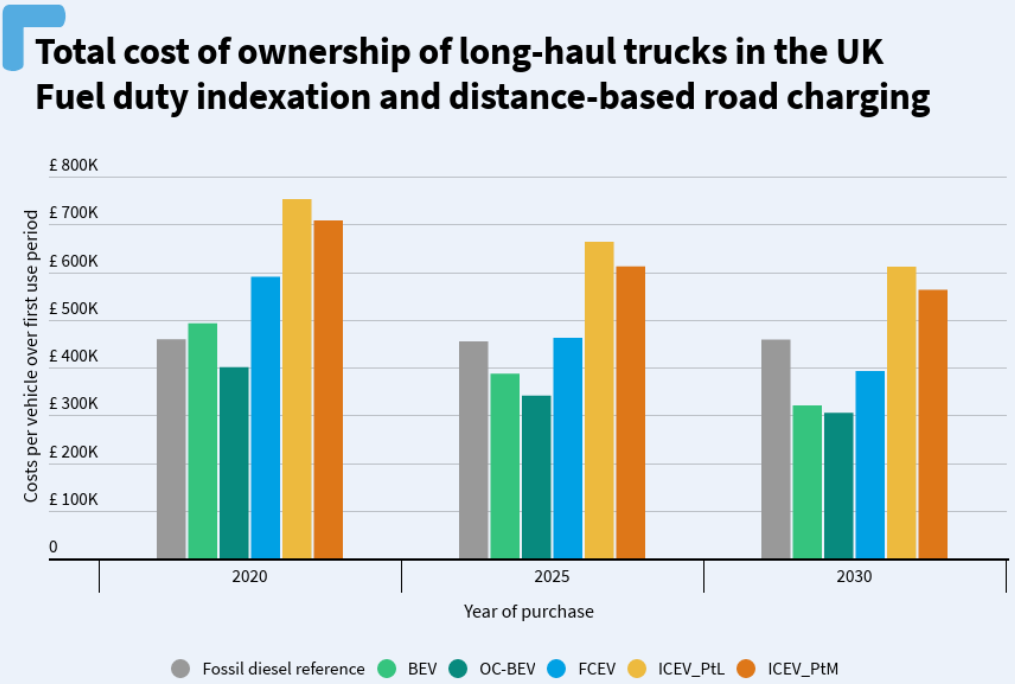


Figure 24: TCO - fuel duty indexation and distance-based road charging

7.4. Charging and refuelling infrastructure

Funding and financing schemes for private companies

The UK is in the process of rolling out a network of charging infrastructure for electric passenger cars but plans for a suitable charging network for commercial vehicles are largely undeveloped. In Germany and California such plans have already been developed and there is an urgent need to incorporate truck charging into the future Comprehensive Spending Review and National Infrastructure Strategy.[229,230] The UK government should also consider introducing funding instruments which support transport companies and the logistics sector to install private and shared infrastructure for depot and destination charging for urban and regional delivery trucks. Transport & Environment has recently published roadmaps for electric truck charging.[231,232]

Such programmes should involve utility companies and provide explicit funding to upgrade the electricity distribution grid, since fleet operators are often unable to bear the additional infrastructure investment costs. For example, California requires the state's utility providers to undertake the necessary grid upgrades for transport-related electrification activities including vehicle charging.[233] As a result, utilities offer infrastructure upgrades at no additional cost for the vehicle operator.[234]

Public-private partnerships

The formation of public-private partnerships with truck manufacturers and logistics companies, such as the *Volvo LIGHTS* project in California, can help overcome initial funding restraints, facilitate the knowledge flow between stakeholders and advance systematic approaches to electrify integrated supply chain networks.[235]

The UK could consider setting up public-private partnerships with vehicle manufacturers and utility companies focusing specifically on public high-power charging infrastructure for regional and long-haul operations along the trunk road network. The upgrade of grid infrastructure alongside the UK's motorway and road network by network operators will also be necessary to roll out high-power charging stations in the megawatt range for battery electric long-haul trucks.

Electric road systems

If electric road systems are to become a reality, they now require concrete political action and closer collaboration between like-minded countries. Currently, the greatest barrier for ERS deployment is the lack of technological harmonisation. What is also needed is further analysis on the cost differences between overhead catenary, conductive and inductive charging systems and static charging and hydrogen alternatives. It is in the interest of the UK and all European countries to develop a mutual understanding on the required steps towards technological harmonisation in order to ensure cross-border interoperability and the technology's long-term success.

Hydrogen refuelling infrastructure

In terms of the deployment of hydrogen refuelling infrastructure for fuel cell electric trucks, targets could be set first for major sea ports to leverage the synergy effects with hydrogen's future role in maritime shipping and exploit its higher cost-effectiveness by cutting down on fuel transport and distribution costs. At this stage the UK could lay the focus on fleet scale trials to test the viability and costs of renewable hydrogen for long-haul trucks.

7.5. Zero-emission urban freight

In terms of air pollution, HGVs are responsible for significant pollutant emissions in urban areas. According to the most recent data available, 18% of NOx and 11% of particulate matter (PM) road transport emissions are caused by HGVs in Greater London.[236]

In this context, the development of a zero-emission city logistics strategy may be beneficial. Larger urban areas should also consider moving from low-emission zones towards introducing zero-emission zones for both light- and heavy-goods vehicles (i.e. vans and trucks) with a view towards 2025. Transitional arrangements for currently registered vehicles until 2030 can help ensure a smooth transition for affected businesses. The Dutch government's agreement to achieve zero-emission city logistics by 2025 with local governments, businesses and research institutions can serve as a blueprint.[237,238] The City of Amsterdam has set out an ambitious Clean Air Action Plan which will make zero-emission light- and heavy-goods vehicles mandatory in much of the city by 2025.[239]

Annex I: Conversion factors and efficiencies

Energy conversion factors

Energy carrier	Lower heating value used	Comment	Source
Diesel	1.00 kg 11.89 kWh	Including 5% biodiesel	European Committee for Standardization (2012). EN 16258. Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers). Retrieved from https://standards.cen.eu/dyn/www/f?p=204:110:0::::FSP_PROJECT,FSP_ORG_ID:32935,6301&cs=135D47751B5FB5269F007FDCEDA13E4B1
	1.00 L 9.97 kWh		
Hydrogen	1.00 kg 33.33 kWh		Adolf et al. (2017). Shell hydrogen study. Energy of the future? Sustainable mobility through fuel cells and H2. Retrieved from https://www.shell.com/energy-and-innovation/new-energies/hydrogen/_jcr_content/par/keybenefits_150847174/link.stream/1496312627865/6a3564d61b9aff43e087972db5212be68d1fb2e8/shell-h2-study-new.pdf
LNG	1.00 kg 12.53 kWh	EU-average methane content of LNG	Edwards et al. (2014). JRC technical reports. Well-to-Tank Report Version 4.a. JEC Well-to-Wheels Analysis. Retrieved from https://publications.jrc.ec.europa.eu/repository/bitstream/JRC85326/wtt_report_v4a_april2014_pubsy.pdf

Currency exchange rates

Currency	Exchange rate	Date	Source
Pound Sterling	1.00 EUR 0.91 GBP	03 July 2020	European Central Bank (2020). ECB euro reference exchange rate: Pound sterling (GBP). Retrieved from https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-gbp.en.html
	1.00 GBP 1.10 EUR		
US Dollar	1.00 EUR 1.12 USD	03 July 2020	European Central Bank (2020). ECB euro reference exchange rate: US dollar (USD). Retrieved from https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html
	1.00 USD 0.89 EUR		

Conversion efficiencies

Energy and vehicle type	Conversion step	Efficiency[xxx]		Source
		2020	2050	
Fossil diesel **ICEV_diesel**	Engine efficiency[xxxi]	42%	48%	Delgado et al. (2017). Fuel efficiency technology in European heavy-duty vehicles: Baseline and potential for the 2020-2030 timeframe. Retrieved from https://theicct.org/sites/default/files/publications/EU-HDV-Tech-Potential_ICCT-white-paper_14072017_vF.pdf
Direct electrification **BEV and OC-BEV**	Electricity transmission and distribution	94%	95%	Worldbank (2014). Electric power transmission and distribution losses for the European Union. Retrieved from https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?l&locations=EU
	Conversion AC/DC	95%	95%	Apostolaki-Iosifidou et al. (2017), Measurement of power loss during electric vehicle charging and discharging, Energy, 127. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360544217303730
	Battery charge efficiency	95%	99%	Peters et al. (2017). The environmental impact of Li-Ion batteries and the role of key parameters – A review. Renewable and Sustainable Energy Reviews. 67. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S1364032116304713
	Inversion DC/AC	95%	95%	Larmanie et al. (2012). Electric vehicle technology explained. 2nd edition. Wiley. West Sussex/UK.
	Motor efficiency	95%	95%	Larmanie et al. (2012).
Compressed hydrogen **FCEV**	Electrolysis[xxxii]	76%	85%	Wachsmuth et al. (2019). Roadmap Gas für die Energiewende – Nachhaltiger Klimabeitrag des Gassektors. Retrieved from https://www.umweltbundesamt.de/sites/de

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[xxx] The stated efficiency rates refer to long-haul tractor trailers. For HGVs of lower weight classes, the rates would remain largely the same except for a slightly lower average brake thermal efficiency (BTE) for ICEVs.

[xxxi] The values indicate the average BTE based on a peak BTE of 45% (2020) and 51% (2050).

[xxxii] There are efficiency differences between different electrolyser technologies. The rates above represent the mean value from the cited literature for low- and high-temperature electrolysis.

				fault/files/medien/1410/publikationen/2019-04-15_cc_12-2019_roadmap-gas_2.pdf
	Transport, storage and distribution incl. compression[xxxiii]	89%	89%	Wachsmuth et al. (2019).
	Hydrogen to electricity conversion	54%	61%	National Research Council (2013). Transitions to Alternative Vehicles and Fuels, The National Academies Press, Washington, DC/US. Retrieved from https://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels
	Inversion DC/AC	95%	95%	Larmanie et al. (2012).
	Motor efficiency	95%	95%	Larmanie et al. (2012).
Power-to-liquid **ICEV_PtL**	Electrolysis	76%	85%	Wachsmuth et al. (2019).
	CO_2 direct air-capture and FT-synthesis[xxxiv]	72%	72%	Ricardo Energy & Environment (forthcoming). Renewable electricity requirements to decarbonise transport in Europe with electric vehicles, hydrogen and electrofuels.
	Engine efficiency	42%	48%	Delgado et al. (2017). Fuel efficiency technology in European heavy-duty vehicles: Baseline and potential for the 2020-2030 timeframe. Retrieved from https://theicct.org/sites/default/files/publications/EU-HDV-Tech-Potential_ICCT-white-paper_14072017_vF.pdf
Liquefied power-to-methane **ICEV_PtM**	Electrolysis	76%	85%	Wachsmuth et al. (2019).
	CO_2 direct air-capture and methanation	73%	73%	Ricardo Energy & Environment (forthcoming).
	Transport, storage and distribution incl. liquefaction	93%	93%	Wachsmuth et al. (2019).

[xxxiii] This refers to compressed hydrogen onboard storage. The fuel can also be liquefied and stored onboard in order to increase volumetric density. However, this would lead to increased storage costs and additional energy consumption due to the liquefaction process boil-off losses. Irrespective of this, if the hydrogen is to be imported from outside Europe, it will need to be liquefied for transportation via tanker vessel and/or distribution via insulated cryogenic tanker truck.

[xxxiv] The chosen DAC method is temperature swing adsorption, also called low-temperature DAC.

	Engine efficiency[xxxv]	42%	48%	Delgado et al. (2017).

Annex II: Cost assumptions

Vehicle costs

Vehicle costs[xxxvi]						
Pathway		**2020**	**2025**	**2030**	**2040**	**2050**
ICEV_diesel	Purchase cost	£ 95,468	£ 98,794	£ 104,309	£ 104,309	£ 104,309
	M&R	£ 16,258 p.a.	£ 16,367 p.a.	£ 16,367 p.a.	£ 16,367 p.a.	£ 16,367 p.a.
	Vehicle taxes	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.
BEV	Purchase cost	£ 296,038	£ 194,564	£ 140,611	£ 140,611	£ 140,611
	M&R	£ 11,404 p.a.	£ 11,404 p.a.	£ 11,404 p.a.	£ 11,404 p.a.	£ 11,404 p.a.
	Vehicle taxes	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.
OC-BEV	Purchase cost	£ 164,704	£ 127,844	£ 103,658	£ 103,658	£ 103,658
	M&R	£ 11,621 p.a.	£ 11,621 p.a.	£ 11,621 p.a.	£ 11,621 p.a.	£ 11,621 p.a.
	Vehicle taxes	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.
FCEV	Purchase cost	£ 224,674	£ 196,243	£ 171,541	£ 157,802	£ 144,663
	M&R	£ 20,907 p.a.	£ 14,879 p.a.	£ 14,879 p.a.	£ 14,879 p.a.	£ 14,879 p.a.
	Vehicle taxes	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.
ICEV_PtL	Purchase cost	£ 95,468	£ 98,794	£ 104,309	£ 104,309	£ 104,309
	M&R	£ 16,258 p.a.	£ 16,367 p.a.	£ 16,367 p.a.	£ 16,367 p.a.	£ 16,367 p.a.
	Vehicle taxes	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.

[xxxv] Assuming dual-fuel CI HPDI technology for ICEVs_PtM with an engine efficiency on par with diesel.

[xxxvi] Excluding residual value, VAT, financing costs and plug-in grant.

ICEV_PtM	Purchase cost	£ 116,153	£ 108,674	£ 114,740	£ 114,740	£ 114,740
	M&R	£ 17,388 p.a.	£ 16,193 p.a.	£ 16,193 p.a.	£ 16,193 p.a.	£ 16,193 p.a.
	Vehicle taxes	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.	£ 861 p.a.

Notes: Purchase costs for long-haul tractor trailers with 44 tonnes GVW. All costs are kept constant after 2030 as it is not possible to make reasoned assumptions beyond this date. Purchase cost includes manufacturing costs due to the glider, conventional powertrain, electric powertrain, fuel cell system, battery, pantograph and fuel storage system and is multiplied with a markup factor of 1.4 to determine the net retail price. Taking into account additional technology costs due the fuel efficiency improvements for ICEVs under the BAU scenario. M&R include costs due to general servicing, urea solution for the exhaust aftertreatment system and the pantograph. Vehicle taxes include registration charge and Vehicle Excise Duty (VED). ICEV_diesel retail price includes additional costs due to fuel efficiency improvements. BEV retail price includes opportunity costs due to additional battery weight before 2030. Residual value, VAT, financing costs and the plug-in grant are excluded.

Sources: T&E calculations based on Kühnel et al. (2018), Meszler et al. (2018), BloombergNEF (2019), Moultak et al. (2017), Hall et al. (2019), U.S. Department of Energy (2019), Driver & Vehicle Licencing Agency (2018), Department for Transport (2018), ACEA (2019).

Battery costs

	2020	2025	2030	2040	2050
Net pack costs per kWh	£ 117	£ 75	£ 49	£ 49	£ 49
Retail pack costs per kWh	£ 163	£ 106	£ 69	£ 69	£ 69
Retail pack costs per kWh (sensitivity)	£ 157	£ 60	£ 40	£ 40	£ 40
Gravimetric energy density at pack level	183 Wh/kg	245 Wh/kg	318 Wh/kg	478 Wh/kg	508 Wh/kg

Notes: Costs are kept constant after 2030. The retail cost includes the same markup factor of 1.4 as for the vehicle costs to determine the net retail price after manufacturing, assembly and distribution costs as well as profit margin. The battery pack gravimetric density values are the low assumptions on the potential for future improvement.

Sources: BloombergNEF (2019), Kühnel et al. (2018), Ricardo Energy & Environment (2019).

Energy consumption

Pathway	in L/100 km				
	2020	2025	2030	2040	2050
ICEV_diesel (tank-to-wheel)	29.86	26.67	23.47	23.47	23.47
ICEV_PtL (tank-to-wheel)	29.86	26.67	23.47	23.47	23.47

	in kWh/km				
BEV (battery-to-wheel)	1.44	1.30	1.15	1.15	1.15
BEV (plug-to-wheel)	1.52	1.36	1.21	1.21	1.21
OC-BEV (pantograph-to-wheel)	1.54	1.40	1.25	1.25	1.25
OC-BEV (from the grid)	1.71	1.55	1.39	1.39	1.39
FCEV (tank-to-wheel)	2.53	2.24	1.95	1.87	1.79
ICEV_PtM (tank-to-wheel)	2.96	2.64	2.33	2.33	2.33

Notes: Energy consumption values for long-haul tractor trailers with 44 tonnes GVW. Values after 2030 are kept constant except for the FCEV which benefits from an increasing fuel cell efficiency until 2050. Taking into account the fuel efficiency improvements of ICEVs until 2030 under the BAU scenario. For OC-BEVs, above values represent the fuel consumption when drawing traction from the overhead lines with and without charging losses; when running on the battery, the BEV (battery-to-wheel) values apply.

Sources: T&E calculations based on Earl et al. (2018), Delgado et al. (2017), Moultak et al. (2017), Kühnel et al. (2018), National Research Council (2013), Volvo (2017).

Renewable electricity and fuel costs

Electricity and electricity-based fuel production in the North Sea		**£-pence/kWh**				
		2020	**2025**	**2030**	**2040**	**2050**
Fossil diesel	Total	4.96	4.96	4.96	4.96	4.96
	Total incl. taxes & levies	10.80	10.80	10.80	10.80	10.80
	Total incl. fuel duty indexation	10.80	11.73	12.60	14.71	17.41
Electricity from offshore wind in the North Sea	Levelised cost of electricity	8.34	7.06	6.54	5.56	4.63
	Transport to the UK	*Grid connection fees included in LCOE*				
	Distribution in the UK	7.15	7.15	7.15	7.15	7.15
	Total	15.50	14.21	13.70	12.71	11.78
	Total incl. taxes & levies	19.67	18.39	17.87	16.89	15.96

Hydrogen from offshore wind in the North Sea	Levelised cost of hydrogen	13.40	11.40	10.40	8.58	6.98
	Liquefaction	6.65	5.32	3.99	3.33	2.66
	Transport to the UK	*not applicable*				
	Distribution in the UK	1.45	1.45	1.45	1.45	1.45
	Total	21.50	18.17	15.84	13.35	11.09
	Total incl. taxes & levies	21.50	18.17	15.84	13.35	11.09
Power-to-liquid from offshore wind in the North Sea	Levelised cost of fuel production	22.73	19.98	17.75	15.17	12.90
	Transport to the UK	*not applicable*				
	Distribution in the UK	0.91	0.91	0.91	0.91	0.91
	Total	23.64	20.89	18.66	16.08	13.80
	Total incl. taxes & levies	29.45	26.70	24.47	21.89	19.62
Power-to-methane from offshore wind in the North Sea	Levelised cost of fuel production	21.54	18.74	16.57	13.96	12.22
	Liquefaction	0.62	0.62	0.61	0.58	0.55
	Transport to the UK	*not applicable*				
	Distribution in the UK	1.00	1.00	1.00	1.00	1.00
	Total	23.16	20.35	18.17	15.53	13.76
	Total incl. taxes & levies	25.13	22.33	20.14	17.50	15.74

Notes: Renewable electricity production from offshore wind in the North Sea according to the reference scenario in the Agora PtG/PtL calculator. LCOE includes grid connection fees. Electricity distribution costs in the UK refer to network and operating costs based on Ofgem. Fossil diesel costs for 2020 are based on the 2011-2020 average fuel price in the UK. Projections for the following years are from the reference scenario in the Agora PtG/PtL calculator. Electricity taxes & levies refer to environmental and social obligation costs, supplier pre-tax margin and other direct costs. For hydrogen, the current fuel duty exemption is maintained.

Sources: T&E calculations based on Agora Verkehrswende et al. (2018), Department for Business, Energy & Industrial Strategy (2020), Gov.uk (2020), Ofgem (2019), Hydrogen Council (2020), Pfennig et al. (2017), Mottschall et al. (2019), Fashihi et al. (2016) and Bünger et al. (2016).

Electricity-based fuel production in North Africa		**£-pence/kWh**				
		2020	**2025**	**2030**	**2040**	**2050**
Hydrogen from solar PV in North Africa	Levelised cost of hydrogen	9.20	8.22	7.40	6.02	4.97
	Liquefaction	6.65	5.32	3.99	3.33	2.66
	Transport to the UK	0.47	0.47	0.47	0.47	0.47
	Distribution in the UK	1.45	1.45	1.45	1.45	1.45
	Total	17.77	15.46	13.31	11.26	9.55
	Total incl. taxes & levies	17.77	15.46	13.31	11.26	9.55
Power-to-liquid from solar PV in North Africa	Levelised cost of fuel production	17.10	15.71	13.74	11.74	10.21
	Transport to the UK	0.02	0.02	0.02	0.02	0.02
	Distribution in the UK	0.91	0.91	0.91	0.91	0.91
	Total	18.02	16.63	14.66	12.66	11.13
	Total incl. taxes & levies	23.83	22.44	20.47	18.47	16.94
Power-to-methane from solar PV in North Africa	Levelised cost of fuel production	16.13	14.65	12.73	10.68	9.65
	Liquefaction	0.62	0.62	0.61	0.58	0.55
	Transport to the UK	0.08	0.08	0.08	0.08	0.08
	Distribution in the UK	1.00	1.00	1.00	1.00	1.00
	Total	17.83	16.35	14.42	12.34	11.28
	Total incl. taxes & levies	19.80	18.32	16.39	14.31	13.26

Notes: Electricity-based fuel production from solar PV in North Africa according to the reference scenario in the Agora PtG/PtL calculator. For hydrogen, the current fuel duty exemption is maintained.

Sources: T&E calculations based on Agora Verkehrswende et al. (2018), Department for Business, Energy & Industrial Strategy (2020), Gov.uk (2020), Ofgem (2019), Hydrogen Council (2020), Pfennig et al. (2017), Mottschall et al. (2019), Fashihi et al. (2016) and Bünger et al. (2016).

Infrastructure costs

Electric charging station				
Parameters		**2020**	**2025**	**2030**
High-power charger (1.2 MW)	Charging time	30 minutes for 400 km range		
	Supplied vehicles per day	10		20
	Service life	15 years		
	Capital expenditure	£ 420,254	£ 380,121	£ 338,657
	Operational expenses per year	£ 4,203 p.a.	£ 3,801 p.a.	£ 3,387 p.a.
Overnight charger (150 kW)	Charging time	8 hours for 800 km range		
	Supplied vehicles per day	0.833		0.909
	Service life	15 years		
	Capital expenditure	£ 67,879	£ 62,942	£ 58,828
	Operational expenses per year	£ 679 p.a.	£ 629 p.a.	£ 588 p.a.
Total infrastructure costs per vehicle per year (high utilisation)		£ 9,469 p.a.	£ 8,707 p.a.	£ 6,260 p.a.

Electric road system				
Parameters		**2020**	**2025**	**2030**
Overhead catenary system	System voltage	1,500 V_{DC}		
	Maximum power consumption per vehicle for traction and battery charging	240 kW		
	Average vehicle speed	80 km/h		

	Installed permanent power per direction	2 MW/km
	Installed permanent substation power	4 MW/km
	Number of supplied vehicles per direction (at 240 kW)	8 vehicles/km
	Number of supplied vehicles per direction at overload capacity (for up to 2 hrs at 240 kW)	12 vehicles/km
	Possible time gap between vehicles	5.40 seconds
	Possible time gap at overload capacity	4.05 seconds
	Service life	20 years
	Capital expenditure per km (both directions)	£ 2.76 million
	Capital expenditure per MW (both directions)	£ 690,101
	Operational expenses per km (both directions)	£ 55,208 p.a.
Total infrastructure costs per vehicle per year (high utilisation)		£ 4,831 p.a.

Hydrogen refuelling station				
Parameters		**2020**	**2025**	**2030**
Mid-sized hydrogen refuelling station	Total refuelling capacity	5,468 kg_{H2}		
	Mean refuelling quantity per vehicle	36 kg_{H2}	32 kg_{H2}	28 kg_{H2}
	Dispenser flow rate	3.6 - 7.2 kg_{H2}/min		
	Supplied vehicles per day	110		166
	Service life	15 years		
	Capital expenditure	£ 6.30 million	£ 5.70 million	£ 5.08 million
	Operational expenses per year	£ 63,304 p.a.	£ 57,018 p.a.	£ 50,799 p.a.
Total infrastructure costs per vehicle per year (high		£ 4,394 p.a.	£ 3,974 p.a.	£ 2,346 p.a.

utilisation)			

LNG refuelling station				
Parameters		**2020**	**2025**	**2030**
Mid-sized LNG refuelling station	Total refuelling capacity	17,000 kg_{LNG}		
	Mean refuelling quantity per vehicle	113 kg_{LNG}	101 kg_{LNG}	89 kg_{LNG}
	Supplied vehicles per day	55		83
	Service life	15 years		
	Capital expenditure	£ 935,822		
	Operational expenses per year	£ 24,509 p.a.		
Total infrastructure costs per vehicle per year (high utilisation)		£ 1,580 p.a.	£ 1,580 p.a.	£ 1,047 p.a.

Notes: Infrastructure costs for long-haul tractor trailers with 44 tonnes GVW. Infrastructure costs are kept constant after 2030. ICEVs_diesel and ICEVs_PtL can use the already established refuelling infrastructure. It is assumed that the investment costs of these petrol stations are already written off and the infrastructure does not need to be replaced after the end of its service life.

Sources: T&E calculations based on Kühnel et al. (2018).

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