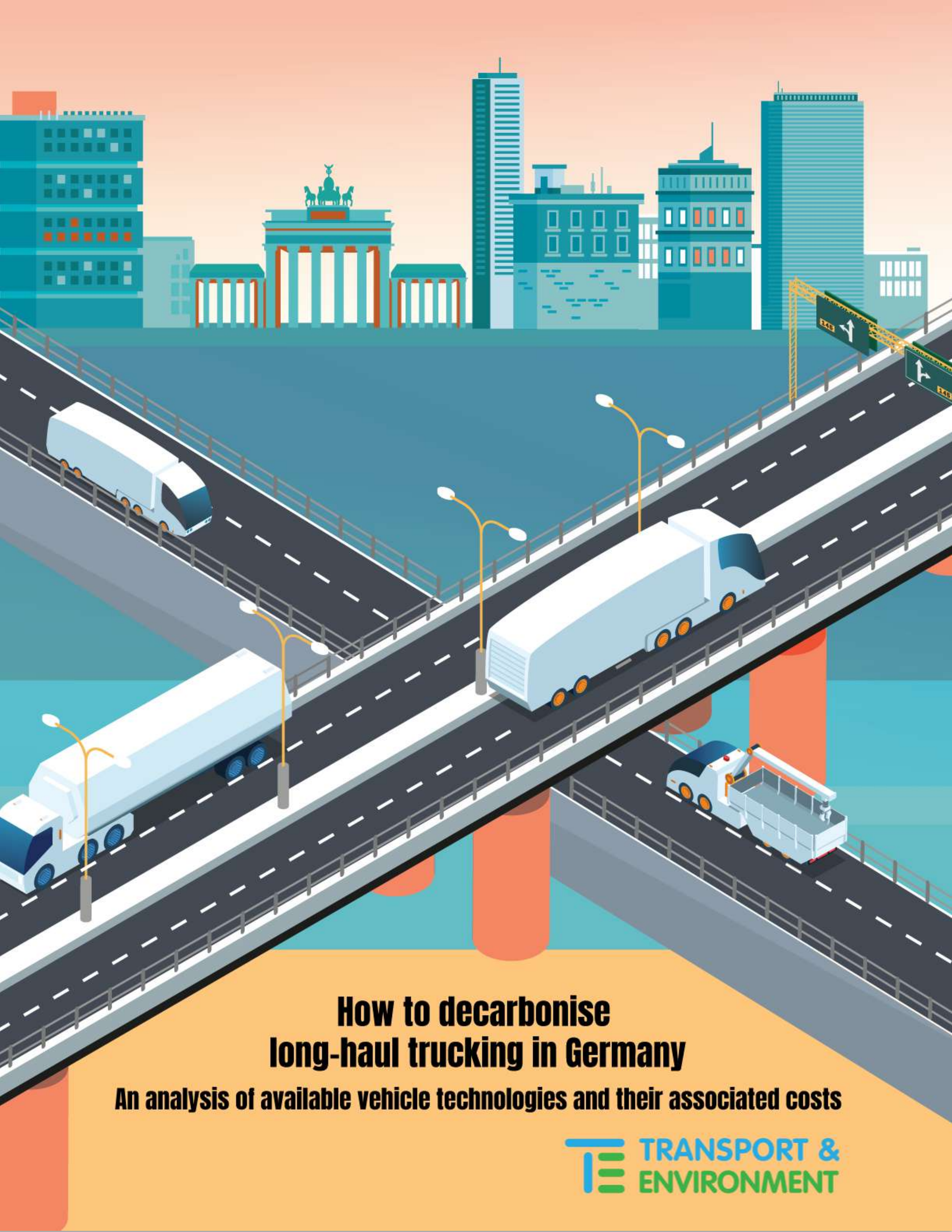

How to decarbonise long-haul trucking in Germany

An analysis of available vehicle technologies and their associated costs

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Executive summary

Efficiency measures such as improving fuel efficiency of conventional diesel trucks, incentivising modal shift to rail and waterways as well as increasing logistics efficiency can contribute to reducing freight emissions in Germany, but will not be sufficient to achieve the country's 2030 and 2050 climate targets. For this, heavy-goods vehicles (HGVs) will need to be entirely decarbonised by 2050 at the latest.

This study analyses the system costs as well as total cost of ownership (TCO) of those vehicle technologies which can decarbonise Germany's long-haul truck fleet. We define long-haul trucking as freight movements on single vehicle trips longer than 400 km. In Germany, 76% of the total road freight activity is performed on single trip distances of up to 800 km which constitutes the minimum range of the vehicle technologies examined in this study.

Notes: Distribution of road freight activity across vehicle trip distance bands in Germany. Trips can last multiple days. The dark green shade illustrates the activity which can be covered by vehicles with 800 km range without recharging or refuelling. The light green shade extends this coverage based on one recharging or refuelling event during the mandatory daily rest period.

Distribution of road freight activity in Germany across trip distances

To be in line with the decarbonisation imperative, long-haul trucks will need to be powered by renewable electricity, whether directly or indirectly in the form of electricity-based fuels. In order to ensure a fair comparison, all technologies were compared based on the condition that they are powered by renewable electricity and can therefore be regarded as zero-emission or CO_2-neutral from a well-to-wheel perspective. Five vehicle technologies were examined:

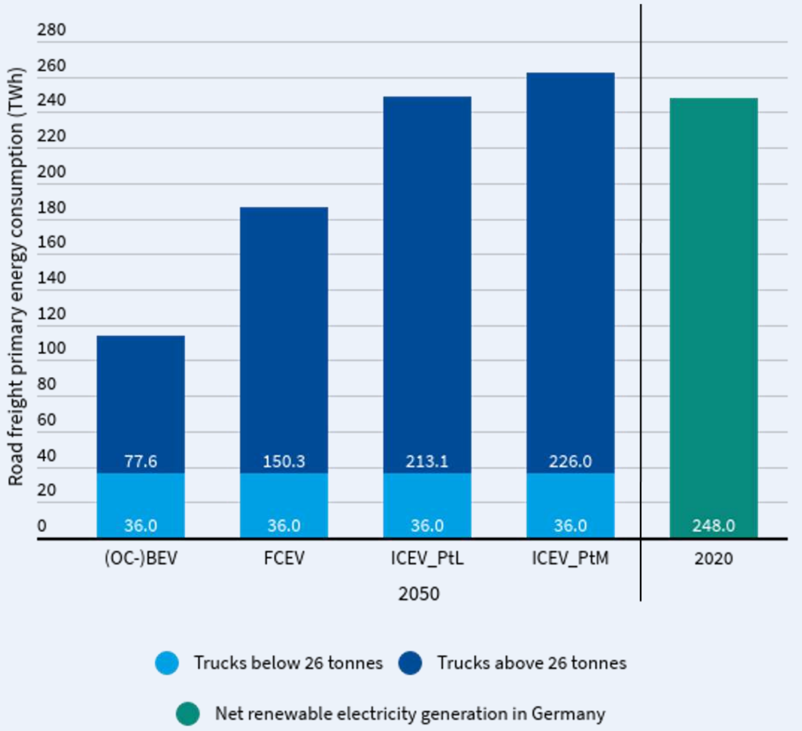
- battery electric vehicles (BEVs),
- battery electric vehicles using an overhead catenary infrastructure (OC-BEVs)

- hydrogen-powered fuel cell electric vehicles (FCEVs)
- diesel vehicles powered by liquid e-fuels (ICEVs_PtL)
- gas vehicles powered by gaseous e-fuels (ICEVs_PtM)

The study reaches the conclusion that, based on today's assumptions, expected market developments and the foreseeable technology cost reductions, battery electric long-haul trucks and those using an overhead catenary infrastructure are likely going to be the most cost-effective pathway to replace the vast majority of today's diesel-powered vehicle fleet and, eventually, reach zero well-to-wheel road freight greenhouse gas (GHG) emissions by 2050.

Additional renewable electricity demand

The vehicle technologies are subject to different conversion efficiency losses and require varying amounts of renewable electricity as input. Directly electrifying trucks is today, and will remain so in the future, at least twice as efficient as renewable hydrogen and around three times as efficient as internal combustion engines running on synthetic e-fuels. In 2050, the direct electrification pathway would require an equivalent of 46% of Germany's 2020 net renewable electricity generation, the hydrogen pathway 75% and the two hydrocarbon pathways 100% and 106%.



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

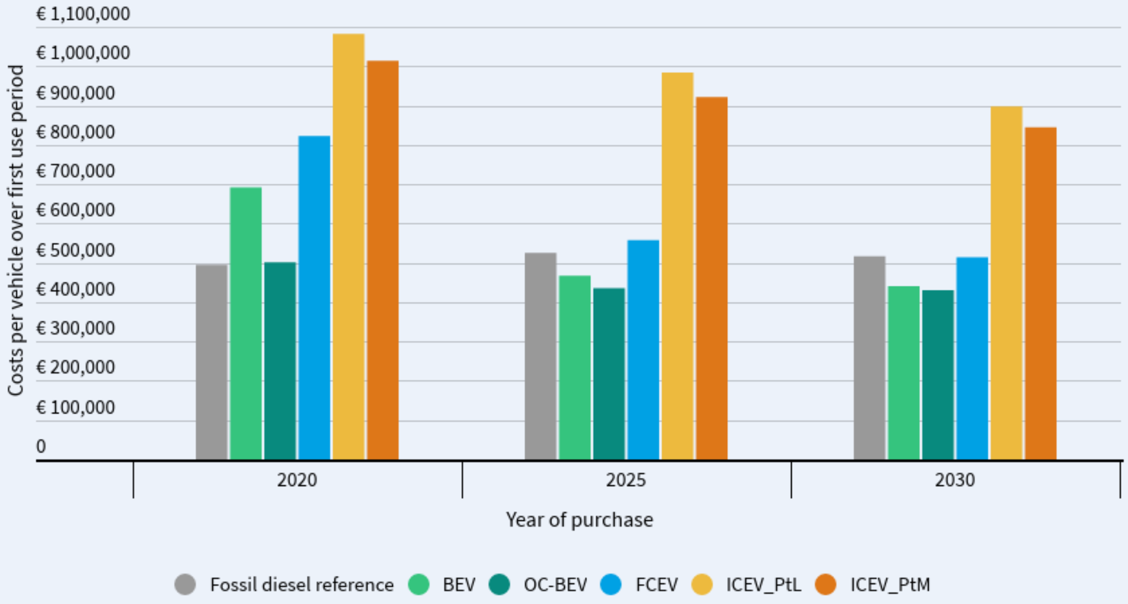
2050 primary energy consumption compared to 2020 net renewable electricity generation

Total cost of ownership

The renewable energy costs 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, road charges and current subsidies, long-haul BEVs and OC-BEVs will likely represent the most cost-effective option in most scenarios included.

Long-haul OC-BEVs may reach TCO parity with fossil diesel trucks before the mid 2020s, BEVs in the mid 2020s and FCEVs around 2030. Long-haul BEVs and OC-BEVs would also likely be cheaper than FCEVs and ICEVs running on electricity-based fuels when those are produced in North Africa under ideal conditions and shipped to Germany.

TCO of long-haul trucks in Germany
Electricity-based fuel production in Europe



Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including total vehicle costs (purchase costs and residual value, maintenance & repairs, vehicle taxes, excl. financing costs and VAT), renewable electricity and fuel costs (incl. grid connection fees, transport and distribution costs as well as taxes and levies), infrastructure costs (at high utilisation) and road charges varied based on the Eurovignette Revision. BEV includes opportunity costs due to additional battery weight until 2025.

TCO - base case with electricity-based fuel production in Europe

Hydrogen fuel cell trucks with longer ranges may be better suited for trip distances longer than 1,200 km. However, these trips only account for 11% of total road freight activity in Germany. There might also be other niche applications where hydrogen trucks may benefit from range- or cost-related advantages such as off-road vehicles like dump trucks for mining operations or vehicles for heavy-load and special road freight movements. Hydrogen trucks could also have operational and cost advantages for drayage applications in and around sea ports due to synergy effects with maritime shipping.

Ultimately, the economic cost-competitiveness of each vehicle technology will depend on how their economies of scale will evolve over the coming decade. Automotive batteries are currently experiencing a self-reinforcing dynamic which will drive down their costs dramatically due to the accelerating ramp-up in the passenger car market and this is soon expected to spill over to the urban and regional delivery truck segment and, subsequently, to long-haul trucking.

Policy recommendations

Road haulage is a business which means that it will require both strong regulation and substantial incentives so that zero-emission alternatives can reach cost parity with conventional diesel trucks. The Federal Government should focus on more stringent regulation both at national and EU-level as well as targeted funding incentives for zero-emission trucks and infrastructure.

Demand for zero-emission trucks

ZEV purchase grant

In Germany, transport companies can receive grants of up to € 40,000 for zero-emission trucks, whereby a maximum 40% of the additional vehicle investment costs is covered. It is welcomed that, pending EU approval, Germany has announced it will cover up to 80% of the additional investment costs with a total funding volume of € 1.16 billion until 2023.

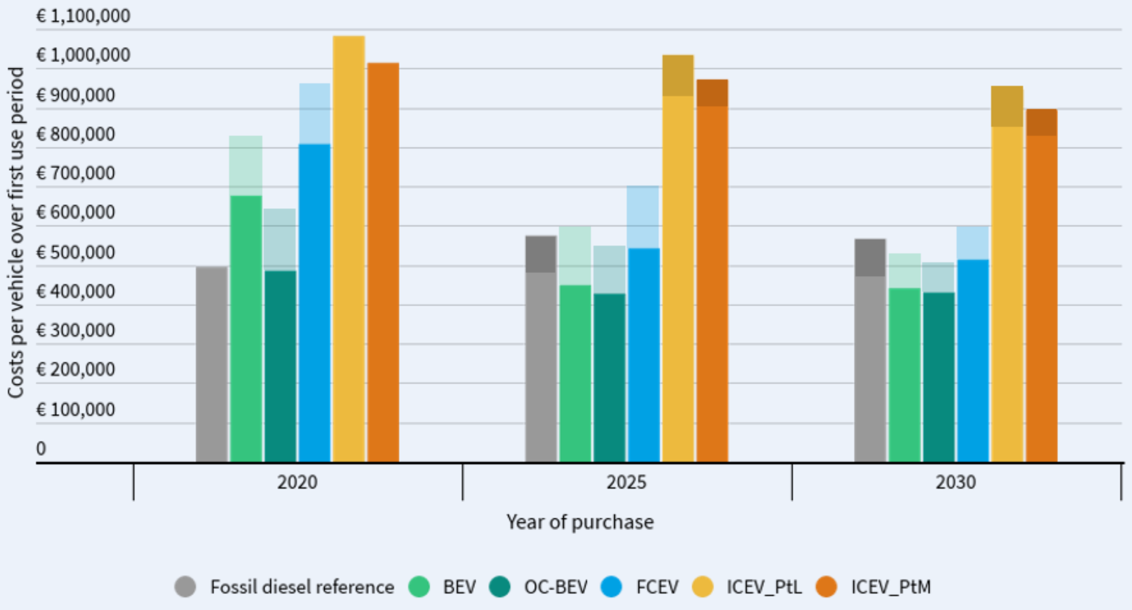
Road charging

Under the revised Eurovignette Directive (currently under negotiation), Germany will have to vary the infrastructure charge from 2023. Germany has announced to vary the infrastructure charge based on CO_2 in combination with an effective CO_2 external cost charge from 2023. Germany should keep the current ZEV exemption from the infrastructure charge until 2025 and reduce it to 75% compared to CO_2 emission class 1 thereafter.

In addition, Germany should levy a CO_2 external cost charge at twice the reference value which is the equivalent to a CO_2 price of € 200/tCO_2. A reimbursement system will likely be introduced as part of the 'Lkw-Maut' revision. Such a reimbursement should only be applied if CO_2 is levied through an external cost charge at twice the reference value.

Germany must end the current toll exemption for gas trucks immediately to not further violate EU law. Under the CO_2 variation and only from 2023 onwards, gas trucks will benefit from a toll reduction on the infrastructure charge. Until CO_2 variation enters into force, Euro VI gas trucks must be tolled at the same level as Euro VI diesel trucks to comply with the current and soon-to-be revised Eurovignette Directive.

In combination with the planned revision of the purchase subsidy, this would have a significant impact on the TCO. By increasing the purchase subsidy funding rate to 80% of the additional investment costs, increasing the funding cap to € 60,000 and revising the road charging scheme as suggested above, long-haul BEVs could possibly reach TCO parity with fossil diesel trucks as early as 2024 and FCEVs soon thereafter.



TCO of long-haul trucks in Germany after purchase subsidy and road charging reform

Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including total vehicle costs (purchase costs and residual value, maintenance & repairs, vehicle taxes, excl. financing costs and VAT), renewable electricity and fuel costs (incl. grid connection fees, transport and distribution costs as well as taxes and levies), infrastructure costs (at high utilisation) and road charges varied based on the Eurovignette Revision. BEV includes opportunity costs due to additional battery weight until 2025.

TCO - after purchase subsidy and road charging reform

Charging and refuelling infrastructure

Alternative Fuels Infrastructure Directive

Germany should advocate for an ambitious revision of the EU Directive on Alternative Fuels Infrastructure (AFID). The Directive should be changed into a Regulation to ensure swift and harmonised infrastructure deployment. The regulatory scope should be limited to zero-emission technology only. Current infrastructure targets for CNG and LNG vehicles should be phased out by 2025 at the latest.

The AFID should set binding targets for the number of charging points per Member State for 2025 and 2030. Germany will need to deploy around 4,000 (semi)-public and destination chargers by 2025 and at least 14,000 by 2030 (excluding public overnight charging). High-power charging (at least 350 kW) should account for between one third and one half of these charging points. Initial deployment of public high-power charging and destination charging in the first half of the 2020s should focus on the hot spots for road freight activity along the TEN-T network, the so-called 'urban nodes', which should be fully covered by 2025.

Long-haul battery electric trucks will require an initial high-power and megawatt charging (MCS) network along the motorways by 2025, at least one site every 100 km by 2027 and, finally, full MCS coverage every 50 km by 2030. For destination charging, all medium and large logistics hubs should have at least one high-power opportunity charger from 2025. In addition, public overnight chargers (150 kW) will be needed at truck parking areas reaching full coverage by 2030.

Financial support for private and public charging infrastructure
Germany has announced an ambitious funding programme for charging and refuelling infrastructure with a total volume of € 4.1 billion until 2023 for both light- and heavy-duty vehicles. As planned, the Federal Government should introduce a dedicated funding instrument to support transport operators for installing depot and destination charging infrastructure for urban and regional delivery trucks. The programme should also provide explicit funding to upgrade the electricity grid since transport operators are often not able to bear the additional grid-related investment costs.

Megawatt charging infrastructure
Public-private partnerships with truck manufacturers, transport operators, utility companies and grid operators are needed to lay the groundwork for the deployment of a country-wide initial megawatt charging (MCS) network from 2025. The recent announcement by a cross-industry consortium to conduct a publicly-funded MCS pilot project by 2023 is an important first step. Germany should consider the funding of similar projects with a specific focus on battery electric long-haul operations along the German trunk motorway network.

Hydrogen refuelling infrastructure

In regards to the deployment of refuelling infrastructure for hydrogen fuel cell trucks, sea ports and their economic hinterland should be prioritised for initial pilot projects. Ports and adjacent industrial clusters represent a no-regret starting point to roll out hydrogen refuelling stations for trucks as this will create synergy effects with hydrogen's future application in the shipping and industry sectors.

Energy taxation

Electricity

Electricity used by commercial road freight vehicles is currently liable in full to taxes, levies and charges. The renewables surcharge ('EEG-Umlage') is now capped to 20% for transport operators using electric buses for regular services and whose electricity consumption amounts to at least 100 MWh per year. This provision should be extended to the transportation of goods by electric trucks for a limited time period when the German Renewable Energy Sources Act is revised again in 2021.

Natural gas

Germany is currently applying an extremely low fuel duty rate to natural gas used as a transport fuel (€ 13.90/MWh) regardless whether it is fossil-derived or sustainably-sourced biomethane. Germany should adjust the reduced rate so that it only applies to sustainable biomethane which is sourced from advanced waste- and residue-based feedstocks.

Diesel

Despite its higher energy and carbon content, diesel fuel is still being taxed at a lower level than petrol. Diesel and petrol fuel duty rates have furthermore been frozen since 2003. The diesel fuel duty rate should be gradually raised until it reaches the equivalent level of petrol on the basis of their respective energy or carbon content. Such a fuel taxation reform needs to take into account the future regulatory design and CO_2 charge level of both the road charging reform and any exemption scheme from the BEHG (see above).

Supply of zero-emission trucks

European CO_2 standards for new HDVs

To overcome the looming supply gap, Germany should advocate for an ambitious review of the CO_2 emission performance standards for new HDVs in 2022 and thereby provide the market signal to truck manufacturers to ramp up the production of zero-emission trucks. The upcoming revision planned for the end of 2022 needs to address a number of shortcomings:

The current average fleet reduction target for 2030 of 30% is wholly insufficient to meet Germany's and the EU's climate targets. A growing part of the 2025 and 2030 targets will be met by accelerating the deployment of ZEVs. The target for 2030 therefore needs to be considerably increased. In addition, the Regulation should set subsequent targets for 2035 and 2040. The EU should adopt a sales phase-out for new ICE trucks with a GVW below 26 tonnes for 2035 and above 26 tonnes by 2040 at the latest.

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 German national law as soon as possible. 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.

Member States were initially legally obliged to transpose this Decision into national law by September 2020 already. The national legislative procedure must now be concluded as quickly as possible so that truck manufacturers have certainty for their future vehicle cab development.

Zero-emission urban freight

The Federal Government should develop a zero-emission city logistics strategy in close coordination with cities and municipalities. Urban areas should consider introducing zero-emission zones for both light-commercial and heavy-goods vehicles, i.e. vans and trucks, with a view towards the second half of the decade. 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.

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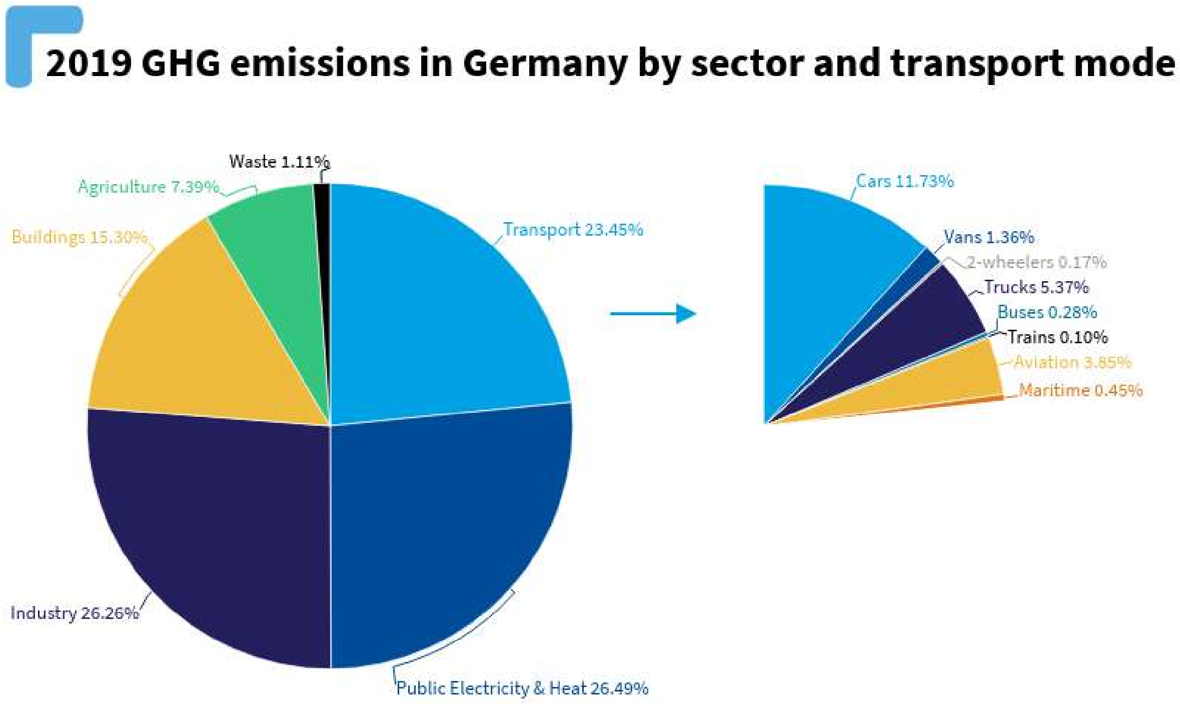
List of acronyms

BEV	Battery electric vehicle
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DAC	Direct air-capture
E-fuels	Electrofuels
ERS	Electric road system
FCEV	Fuel cell electric vehicle
FT-synthesis	Fischer-Tropsch synthesis
gCO_2e	Grams of carbon dioxide equivalent
GVW	Gross vehicle weight
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 e-fuels (synthetic e-diesel)
ICEV_PtM	ICEVs using gaseous e-fuels (synthetic e-methane)
LCOE	Levelised cost of electricity
LCOH	Levelised cost of hydrogen
LNG	Liquefied natural gas
Mt	Megatonnes
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
VECTO	Vehicle Energy Consumption Calculation Tool
vkm	Vehicle-kilometres
WTT	Well-to-tank
WTW	Well-to-wheel
Z(L)EV	Zero- (and low-)emission vehicle

1. Introduction

Transport is one of the major emitting sectors in Germany with total annual emissions amounting to 196 megatonnes of CO_2 equivalent (Mt CO_2e) and accounting for 23% of total 2019 greenhouse gas (GHG) emissions when international aviation and shipping are included. Road transport represents 80% of all transport emissions, of which around 28% are due to heavy-goods vehicles (HGVs).



Notes: Assuming a 95/5% split between truck and bus GHG emissions.

Sources: EEA (2019).

Figure 1: 2019 GHG emissions in Germany by sector and transport mode

Under the Federal Climate Change Act, Germany has to reach an overall GHG emission reduction of at least 55% until 2030 against 1990 levels and, eventually, net-zero GHG emissions by 2050.[1] In addition, Germany's Climate Action Programme sets a target to electrify (directly or based on electricity-based fuels) 30% of HGV vehicle-kilometres (vkm) by 2030.[2] The country must now swiftly reduce and, eventually, eliminate emissions from all transport modes, including road freight, by mid-century.[i] Emissions from the road freight sector pose a major stumbling block. Despite fluctuations, road freight emissions in Germany have overall increased over the past 30 years (see Figure 2). Failing to quickly reduce road freight emissions and eventually eliminate them would make Germany's climate targets all but impossible to attain.

Notes: EUTRM modelling based on the most recent available EEA data from 2019. GHG emissions between 2019 and 2020 are kept constant. Assuming a constant 95%/5% split between GHG emissions from trucks and buses.

Sources: T&E calculations based on EEA (2019).

Figure 2: GHG emission reduction trajectory of the German road freight sector

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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 compensate for unavoidable emissions in other hard-to-abate sectors including industry and agriculture.

In 2019, around 750,000 rigid and articulated trucks above 3.5 tonnes gross vehicle weight (GVW) were registered in Germany.[3] Around 85,000 HGVs are newly registered every year. More than 99% of today's HGV fleet runs on conventional diesel.[4] In addition to the domestically registered vehicle fleet, a further number of foreign-registered vehicles are moving goods within and across Germany too.

The purpose of this study is to analyse the available vehicle technologies which can fully decarbonise Germany's long-haul truck fleet as well as their associated system and user costs. The system costs refer to the costs from manufacturing, assembling and selling the vehicle, producing, transporting and distributing the electricity and renewable fuel as well as constructing and maintaining the charging and refuelling infrastructure. The system costs exclude taxes, levies, road charges and subsidies. This has been a deliberate choice in order to better assess the true techno-economic costs for each vehicle technology which need to be borne by the society, i.e. by manufacturers, operators, consumers and the public sector. By contrast, the user costs, also called total cost of ownership (TCO), take into account taxes, levies, charges and subsidies based on the current legislation in Germany.

Efficiency measures such as improving the fuel efficiency of conventional diesel trucks, incentivising modal shift to rail and waterborne freight as well as optimising logistics efficiencies through digitalisation can contribute to reducing inland freight emissions and their potential should be exploited to the extent feasible.

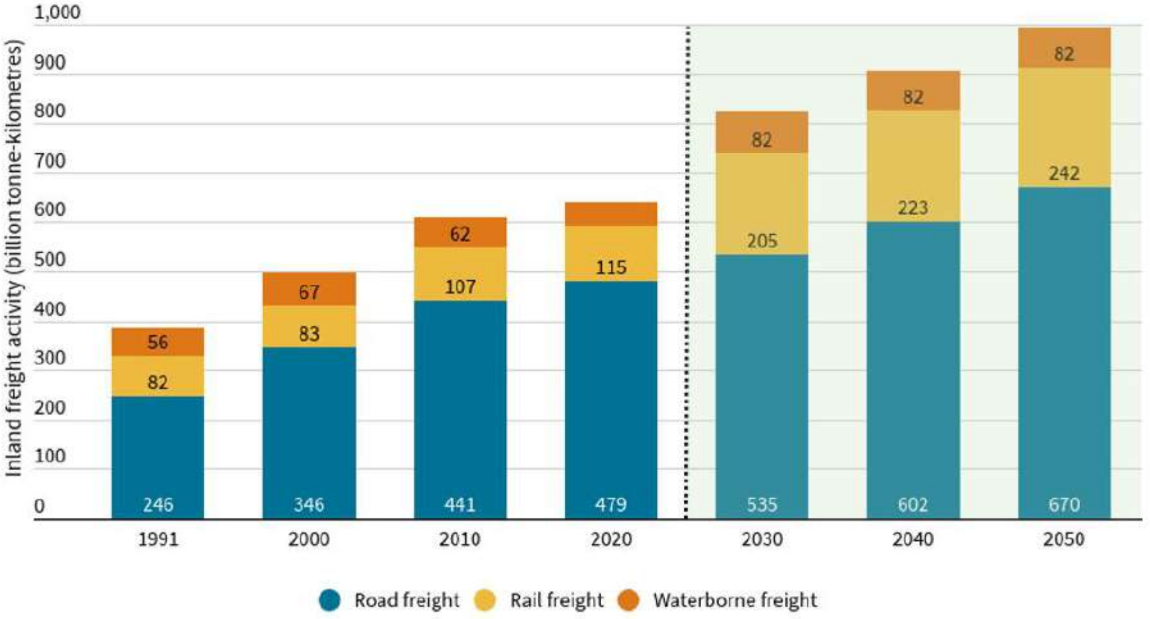
However, as official government projections show, freight activity is expected to continue to grow in the future. Efficiency measures on their own are therefore inadequate to fully decarbonise the inland freight sector by 2050. Recent analysis by Transport & Environment has shown that efficiency measures including increased fuel efficiency of diesel trucks, modal shift and improved logistics efficiencies can help France and the United Kingdom to reduce freight-related emissions somewhat but that they are needed in addition to the full decarbonisation of the truck fleet by changing the vehicle technology and the energy vector in order to reach their climate targets.[5,6]

In other words, it is not about doing one or the other but, instead pursuing both at the same time. Significant increases in rail and waterborne freight capacity as well as further truck fuel efficiency improvements must come in addition to decarbonising urban, regional and long-haul trucking.

2. The inland freight sector in Germany

Inland freight activity in Germany has been characterised by continuous and steady growth over the past 30 years and more than two thirds of it has been carried out by trucks. Based upon conservative assumptions, it is expected that freight activity will continue to rise in the future. Figure 3 summarises the historical development and future projection of future inland freight demand in Germany based on historical data and projections by BMVI (2008), Öko-Institut (2014), Intraplan Consult et al. (2014), Intraplan Consult (2020), BMVI (2020) and Nationale Plattform Zukunft Mobilität (2020).[7,8,9,10,11,12]

The freight demand projections already take into account an ambitious shift of goods to rail and waterborne freight which will require almost a doubling of their respective transport capacity by 2030 to achieve the Federal Government's self-imposed modal shift target (see Figure 4).[13]



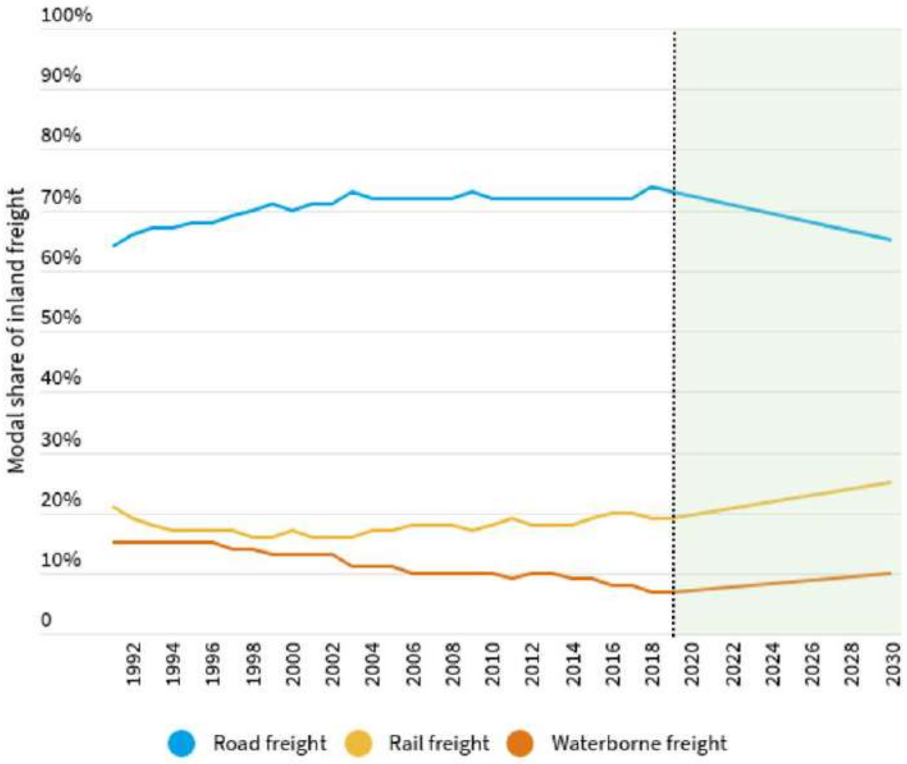
Notes: Derived historical and projected inland freight activity based on the literature and targets of the Federal Government. Excluding inland freight activity of aviation and pipelines.

Sources: T&E calculations based on BMVI (2008), Öko-Institut (2014), Intraplan Consult (2014), Intraplan Consult (2020), BMVI (2020), NPM (2020).

Figure 3: Historical and projected inland freight activity based on government targets

Multiple reasons help explain the historical increase in overall freight activity as well as the low modal share of rail and waterborne freight compared to road. 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 may develop in the future.[14]

For distances up to 500 km, moving goods by road is often superior to rail in terms of cost, time, flexibility and adaptability.[15] Rail freight is highly dependent on the type of goods being transported and more suitable for bulk commodities. 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.[16] Growth potential will only be fully utilised if the infrastructure is improved and rail freight is made more reliable and flexible, for example by digitising the rolling stock, increasing average train speed as well as their length and promoting combined and intermodal transport.



Notes: Excluding inland freight activity of aviation and pipelines.

Sources: T&E calculations based on BMVI (2008), Öko-Institut (2014), Intraplan Consult (2014), Intraplan Consult (2020), BMVI (2020) and NPM (2020).

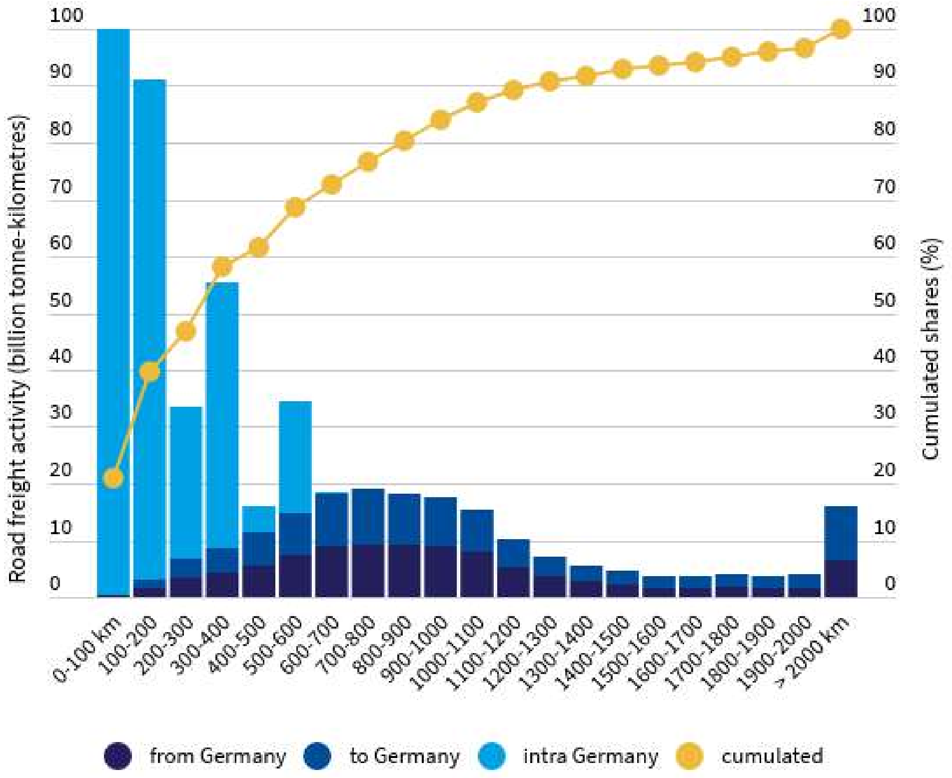
Figure 4: Historical and projected inland freight modal split based on Government targets

Waterborne freight suffers from similar structural disadvantages in terms of cost, time, flexibility and adaptability as is the case for rail. For waterborne transport to be time-effective and economically viable, significant and continuous infrastructure investment in the waterway network is required. 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. Road haulage costs will also need to increase to better account for externalities and make rail and waterways more cost-competitive.

Road haulage is the preferred mode for unit load freight and faces practically no cross-border barriers in Europe. It should be expected that the current trend towards more complex supply chains and a greater transport intensity as a result of the internationalisation of production processes may continue in the coming decades.[17]

It should be noted that the current level of freight transport intensity may not necessarily hold in the future due to, for example, changes in societal and consumption behaviour. 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 order to assume a conservative estimate of future freight demand, but could help make a contribution to the decarbonisation of the sector.

The majority of road freight activity measured in tonne-kilometres (tkm), a good proxy for CO_2 emissions, is moved on vehicle trips below 400 km and is handled by urban and regional delivery trucks (see Figure 5). Long-haul freight movements account for a smaller share of road freight activity, though face the biggest challenges to decarbonise.



Notes: Distribution of road freight activity across vehicle trip distance bands in Germany. Trips can last multiple days.

Sources: T&E calculations based on ETISplus (2010) and calibrated based on Eurostat (2018).

Figure 5: Distribution of road freight activity in Germany across trip distances

3. Available vehicle technologies

There is a need to shift away from fossil fuels towards zero-emission or CO_2-neutral technology to decarbonise the road freight transport sector in Germany. Trucks, similarly to the rest of the economy, will need to run on clean, renewable electricity, whether directly through electrification or indirectly in the form of electricity-based fuels. The available technologies require different amounts of additional renewable electricity as input and vary in their system and user costs. These technologies include:

- Battery electric vehicles
- battery electric vehicles using an overhead catenary infrastructure
- hydrogen-powered fuel cell electric vehicles
- diesel vehicles powered by liquid synthetic e-fuels
- gas vehicles powered by gaseous synthetic e-fuels

The first three options require a rapid change and scale-up of new vehicle technology and dedicated infrastructure. The fourth option does not require changes to the powertrain technology as it is a drop-in fuel which would gradually replace fossil diesel through a fuel blending mandate. As such, existing conventional diesel trucks could run on this e-fuel. The fifth technology option requires modifications to the powertrain, a roll out of dedicated infrastructure, as well as a fuel blending mandate.

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 typically perform single trip distances of up to 400 km. In Germany, 58% of road freight activity comprises trip distances of up to 400 km (see Figure 5).[ii] Direct electrification of this transport activity based on battery electric trucks is not only technically feasible but is soon going to reach cost parity with fossil diesel trucks from a total cost of ownership (TCO) perspective. Battery-electric urban- and regional delivery trucks are already or soon will be in series production such as Daimler's FUSO eCanter and eActros, Volvo's FL and FE Electric, DAF's CF and LF Electric, MAN's eTGM and Renault's D Z.E.[18,19,20,21,22,23]

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 trucks with a typical GVW of up to 26 tonnes, battery electrification will be the most cost-competitive pathway in the future.

Which of the technologies will prevail in the long-haul road freight sector, typically comprising articulated vehicles, i.e. tractor-trailers, with 40 tonnes GVW, is less certain. All potential technologies are at the beginning of the techno-economic learning curve and not yet cost-efficient, let alone cost-competitive with conventional diesel trucks. The purpose of this study therefore is to analyse the vehicle technologies and their costs which are available to decarbonise long-haul trucking.

[ii] T&E calculations based on ETISplus (2010) and calibrated based on Eurostat (2018).

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 energy costs. In the case of passenger cars and vans, a large-scale transition towards battery electric vehicles is now widely regarded as the most cost-effective and fastest pathway to achieve full decarbonisation. The production of battery electric cars and vans is currently ramping up and their market uptake will accelerate in the coming years.

The development of battery technology is advancing and costs are falling. Besides improvements in the manufacturing processes, it is expected that the chemical composition of (post-)lithium-ion battery cells, i.e. the cathode, anode, electrolyte and separator materials, will be further optimised, thereby improving the gravimetric and volumetric energy density, pack weight, cycle life and longevity of batteries as well as enabling sustainable raw material sourcing, second life in stationary storage applications and, eventually, recycling.[24]

Direct electrification of HGVs, which includes battery electric vehicles (BEVs) and those using an overhead catenary infrastructure (OC-BEVs), provides for superior energy efficiency. Both use a (differently-sized) battery pack and an electric powertrain but require different charging infrastructure. Higher vehicle purchase costs due to the onboard battery pack are compensated for by lower operating costs during the vehicle's lifetime. An electric powertrain offers advantages compared to conventional combustion engines. It emits no exhaust and thus eliminates carbon dioxide (CO_2) and air pollutant emissions at the tailpipe. Also, an electric powertrain is made of fewer components and moving parts and therefore requires less maintenance and repairs compared to an internal combustion engine or a fuel cell stack.

3.1.1. Battery electrification

The battery-to-wheel energy consumption is based on Earl et al. and amounts to 1.52 kWh/km in 2020 for a non-optimised cab-over-engine design and 1.15 kWh/km by 2030 for an optimised tractor design cruising at EU-specific motorway speeds of 80 km/h[25,iii] This is achieved through efficiency improvements by reducing the rolling resistance, aerodynamic drag and vehicle curb mass through lightweighting of a 40-tonnes tractor trailer and by taking into account regenerative braking. The

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[iii] Battery-to-wheel energy consumption determines the onboard energy storage capacity which is required to reach the maximum range without recharging. To calculate the electricity consumption, i.e. the energy costs of the BEV, additional losses in the charging equipment need to be taken into account. The respective energy consumption values measured from the grid, i.e. 'plug-to-wheel', are 1.60 kWh/km in 2020 and 1.21 kWh/km from 2030 onwards (see Annex).

average motorway speed of tractor trailers in Germany is likely below the legal speed limit of 80 km/h when accounting for speed limits, construction sites and congestion.[26]

The assumptions represent a reasonable mean value compared to literature references and industry announcements: Moultak et al. as well as 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 higher U.S.-specific maximum motorway speed of 105 km/h.[27,28] Tesla has announced an energy demand of 'less than 1.24 kWh/km' for its Semi truck (also at 105 km/h).[29]

We define long-haul trucking as freight movements on single vehicle trips longer than 400 km. Long-haul tractors require a larger onboard battery for a minimum daily range of around 500 to 800 km and in a few cases more than that. In Germany, 76% of the total road freight activity is performed on single trip distances of up to 800 km (see Figure 5).[iv]

The BEV included in the cost analysis has a nominal (i.e. gross) battery capacity of 1,351 kWh in 2020 (decreasing to 1,022 kWh by 2030 due to energy consumption improvements) for a maximum range of 800 km without recharging.[v] In practice, the maximum operational range without recharging will be around 720 km in order to account for a reasonable safety margin for reaching the next charging location.

To ensure the battery's longevity, the maximum depth of discharge (DoD) is presumed to be 90% which results in a usable (i.e. net) battery capacity of 1,216 kWh in 2020 (decreasing to 920 kWh by 2030). Real-world data suggests an average DoD of around 90% for light-duty vehicles.[30] The specific energy density of the onboard battery pack is assumed to increase from 183 Wh/kg in 2020 to 318 Wh/kg by 2030.[31] This estimate by Ricardo Energy & Environment is consistent with assumptions from other literature sources.[32,33,34] Industry leaders have indicated that such battery performance may actually be reached sooner than widely anticipated.[35]

The onboard battery pack results in a gross additional vehicle weight of 7.4 tonnes in 2020, 4.8 tonnes in 2025 and 3.2 tonnes in 2030. Germany is about to transpose the recent changes to the EU Weights & Dimensions Directive into national law which means that any additional zero-emission powertrain weight will be compensated for by up to 2 tonnes through the ZEV weight allowance.[36] The allowance combined with the net weight savings from replacing a conventional with an electric powertrain (2.4

[iv] T&E calculations based on ETISplus (2010) and calibrated based on Eurostat (2018).

[v] 2020 values for the BEV should be understood as hypothetical values as these vehicles do not currently exist on the market.

tonnes) would result in a net payload loss of around 3.0 tonnes and, consequently, a weight penalty for the BEV in 2020. With increasing energy density of the battery pack and additional mass reduction through lightweighting of the tractor, this issue will no longer be relevant from the second half of the 2020s.[vi] Table 1 illustrates this for the year 2025.

Parameter		Formula	Value	Source
a	Battery-to-wheel energy demand in 2025		1.34 kWh/km	Earl et al. (2018)
b	Maximum range without recharging		800 km	-
c	Battery maximum depth of discharge		90%	T&E calculations
d	Required nominal battery capacity in 2025	a x b / c	1,187 kWh	-
e	Specific energy density at pack level in 2025		245 Wh/kg	Ricardo Energy & Environment (2019)
f	Battery pack weight	d / e	4,844 kg	-
g	Weight of electric axle (including electric motor, inverter and gearbox)		600 kg	Hall et al. (2019)[37]
h	Total weight of electric powertrain	f + g	5,444 kg	-
i	Weight of conventional powertrain and fluids in diesel tank		3,000 kg	Sharpe (2019)
j	**Net additional weight**	**h - i**	**2,444 kg**	-
k	Maximum additional ZEV weight allowance under the EU Weights & Dimensions Directive		(up to) 2,000 kg	European Union (2019)[38]

[vi] T&E calculations.

l	**Net payload loss**	**j - k**	**444 kg**	-

Table 1: Illustrative payload loss calculation for 2025. Adapted from Sharpe (2019)

The capacity of lithium-ion batteries degrades over time depending on various factors such as ambient temperature, the charge rate (or C-rate) and the number of full cycles. A battery thermal management system regulates the temperature level and distribution and, thereby, optimises cell longevity. The typical C-rate at which the BEV will be charged during charging events in the megawatt range amounts to around 1C which is sufficiently low to ensure long-term cell lifetime.

The full cycle life describes the number of equivalent full charge-discharge cycles throughout a battery's lifetime. Today, the lifetime for a battery electric car corresponds to at least 1,000 full cycles.[39] Recent research findings suggest that advanced lithium-ion cell chemistries can preserve a 90% capacity retention for up to 3,000 full cycles.[40] In line with Harlow et al. and Kühnel et al., it is assumed that the BEV's large onboard battery can sustain a cycle life of 1,250 full cycles in 2020, and that it linearly increases to 1,750 cycles by 2030. The BEV runs 889 km per equivalent full cycle. This translates to an overall battery lifetime of 1.1 million km in 2020 and 1.5 million km in 2030 after which the battery is considered to be depleted. This is theoretically sufficient to cover (at least) the first two use periods of a long-haul truck's lifetime.

Long-haul battery electric trucks, whose routes involve multi-day intercity travel, will need to rely on a comprehensive charging infrastructure network along the motorway with an acceptable density. Charging can be done either more slowly overnight or through high-power opportunity charging during the driver's breaks. The assumed charging times are aligned with EU rules on driving times and rest periods in order to avoid operational downtime costs. 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.[41] Based on this and an (optimistic) 80 km/h average vehicle speed, one single driver can perform a single distance of no more than 360 km between mandatory breaks and a maximum distance of no more than 720 km per day.

Based on Kühnel et al., the cost analysis assumes high-power chargers with an output of 1.2 megawatt (MW) to recharge for a maximum range of 400 km in no more than 45 minutes and overnight chargers with a power output of 150 kW to fully charge the battery in around 8 hours.[42]

It should be noted that such high-power chargers would cause significant additional power demands and require a connection to the medium-voltage grid and possibly grid capacity reinforcements.

CharIN, the industry's standardisation initiative, is currently developing the 'Megawatt Charging System' (MCS), a high-power charging standard for commercial vehicles with up to 4.5 MW.[43] Charging BEVs with overnight chargers, supplemented by opportunity charging during the day with stationary battery storage, could be an effective load-levelling strategy to draw electricity from the grid when overall demand is low and thereby help balance intermittent electricity generation from a renewables-based power grid.[44]

3.1.2. Overhead catenary system

Downsizing the onboard battery and charging the vehicle dynamically during operation through an electric road system (ERS) on the most-frequented parts of the motorway network can be an alternative to static charging. 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 be a cost-effective and complementary solution to electrify the long-haul truck segment.[vii] The different ERS technologies have their specific advantages and drawbacks, whereas some regard the overhead line concept as currently the most mature technological option.[45] The overhead catenary technology is currently being tested in field trials on three parts of the German road network and was chosen for the cost analysis.[46,47] Kühnel et al. provide cost estimates based on, amongst other sources, the ENUBA projects funded by the German Federal Environment Ministry.[48,49]

The battery-to-wheel energy demand of the OC-BEV is identical with the BEV values after taking into account the weight difference due to the lighter battery pack and two additional deviations according to Siemens: The extended pantograph leads to an increased energy consumption of 0.10 kWh/km due to increased aerodynamic drag, and additional charging losses of 10% which occur between the medium-voltage grid and the overhead contact wire.[50] The resulting values are 1.54 kWh/km (2020) and 1.25 kWh/km (2030) measured from the pantograph and 1.71 kWh/km (2020) and 1.39 kWh/km (2030) measured from the grid. When operating in battery-only mode and with retracted pantograph on the non-electrified sections of the road network, the values are equivalent to those of the BEV after subtracting the difference in battery weight (see vehicle energy consumption values in the Annex).

OC-BEVs have a smaller onboard battery which can be charged while the vehicle is drawing power from the overhead lines and allows for electric autonomy when driving on non-electrified parts of the road network. The OC-BEV included in the cost analysis has a battery capacity between 320 kWh (2020) and 256 kWh (2030) allowing for a range of up to 200 km when operating disconnected from the overhead

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[vii] Overhead lines could technically also be used by vehicles with hybrid electric powertrains (OC-HEVs) as is the case today for the field trials in Germany. This option was not considered in this study since it is expected that hybrid diesel vehicles using ERS will likely be an exception.

lines.[viii] According to Wietschel et al., more than 95% of tractor trailer trips off the German motorway network are shorter than 100 km.[51] A battery-only range of 200 km is therefore sufficient to bridge smaller and larger electrification gaps and the distance between the motorway and the place of (un)loading as well as to ensure operational flexibility. 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 (e.g. bridges or tunnels). Taking into account the mileage share on the electrified network (80%), this amounts to a 72/28% mileage split between electricity drawn from the overhead lines and from the onboard battery to propel the electric motor.

As for the BEV, it is assumed that the OC-BEV's battery can sustain a cycle life of 1,250 full cycles in 2020 and 1,750 cycles in 2030. The OC-BEV runs 222 km per equivalent full cycle when drawing only electricity from the onboard battery. This translates to an overall battery lifetime of 990,000 km in 2020 and 1.4 million km in 2030 after which it is considered to be depleted. This is theoretically sufficient to cover (at least) the first two use periods of a long-haul truck's lifetime.

The key market barrier to an ERS is a, potentially, reluctant infrastructure ramp-up due to inertia in the market and, initially, higher up-front capital expenditure costs. The technology needs to be harmonised across Europe and its deployment closely coordinated between all involved stakeholders to ensure cross-border interoperability. Similarly to the charging infrastructure for BEVs, significant additional power demand may be placed on the medium-voltage power grid, possibly requiring in parts grid reinforcements.[52]

3.2. Renewable hydrogen

Hydrogen is considered as a potential energy carrier for long-haul road freight. Fuel cell electric vehicles (FCEVs) can be zero-emission from a well-to-wheel (WTW) perspective if the required hydrogen fuel is produced from renewable electricity instead of steam methane reforming (SMR) from natural gas. Fossil-derived ‘blue' hydrogen requires carbon capture and storage (CCS) which would allow to capture up to 90% of downstream emissions if the most advanced technology (autothermal reforming, ATR) is used.[53] However, around 25% of total natural gas lifecycle emissions are due to fugitive emissions caused upstream which continue to be emitted when producing blue hydrogen.[54] This leaves hydrogen produced from renewable electricity, so-called 'green' hydrogen as the only viable production method to achieve zero well-to-wheel GHG emissions.

[viii] 2020 values for the OC-BEV should be understood as hypothetical values as these vehicles do not currently exist on the market.

Renewable hydrogen is produced by an electrolyser which splits water into hydrogen and oxygen using renewable electricity. The electro-chemical conversion in the vehicle's fuel cell generates electricity which is stored in a smaller onboard battery and propels an electric motor. The advantages are the lack of tailpipe CO_2 and air pollutant emissions, relatively short refueling times and possibly longer driving ranges. The key challenges are the well-to-wheel energy conversion losses, the high vehicle technology costs, the low volumetric energy density of hydrogen, the need to develop the necessary fuel distribution and refuelling infrastructure, and an increased likelihood to rely more on fuel imports from outside Europe due to a higher primary renewable electricity demand.

The energy demand is identical for both the FCEV and BEV as they share the same vehicle characteristics and powertrain components with the exception of the electrical plug, fuel cell stack and hydrogen storage tank. That means that the same level of efficiency improvements were assumed as for the BEV and OC-BEV (reducing rolling resistance, aerodynamic drag and vehicle curb mass). The difference between the FCEV and BEV in terms of energy demand is due to the differences in battery weight as well as the additional conversion losses when converting the hydrogen in the fuel cell to electricity (54% average conversion efficiency in 2020, 56% in 2030 and 61% in 2050).[55] This results in 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 compare well to Moultak et al., Daimler and Hyundai.[56,57]

FCEVs have a fuel cell stack, a smaller onboard battery pack to buffer electricity for motor peak loads and a hydrogen storage tank with either compressed or liquefied hydrogen. Compression at 350 or 700 bar is the technically most mature and proven storage possibility.[58] Compression results in lower energy conversion losses compared to liquefaction. Liquefying the hydrogen would increase the volumetric storage density and reduce the weight of the tank material but also lead to higher energy losses of 25% to 35% and require more expensive cryogenic thick-walled storage tanks.[59,60] For the cost analysis, the FCEV was equipped with a PEM fuel cell stack with a rated power output of 240 kW, an onboard battery pack with 127 kWh and a compressed fuel tank at 700 bar with a weight between 1.3 and 0.9 tonnes depending on the vehicle's energy consumption and tank size (61 kg_{H2} decreasing to 47 kg_{H2} by 2030).[ix] Based on the U.S. Department of Energy, the hydrogen dispenser flow rate is estimated to be between 3.6 and 7.2 kg_{H2} per minute which ensures refuelling times of less than 20 minutes when the tank is completely empty.[61]

If the hydrogen is to be produced outside of Europe due to lower renewable electricity costs, it would need to be compressed and transported through an inter-continental transmission pipeline network or

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[ix] 2020 values for the FCEV should be understood as hypothetical values as these vehicles do not currently exist on the market.

liquefied and transported via cryogenic tanker vessel to Germany which would entail considerable additional energy conversion losses.[62] Other overseas transport options include the use of hydrogen carriers such as ammonia or liquid organic hydrogen carriers (LOHCs) which would be easier to transport but would lead to additional conversion losses.[63]

Unless a comprehensive domestic distribution pipeline network was made available in the mid-term future, the domestic distribution from the production site or the import terminal (such as a sea port) would be handled by cryogenic tanker trucks which deliver liquefied hydrogen to the refuelling station where it can be either used directly in its liquefied state or gasified again.[64,65] Another option is the decentralised production of renewable hydrogen next to the refuelling station from either on-site electricity generation or dedicated renewable electricity through a power purchase agreement (PPA), perhaps with temporary stationary battery storage to reduce peak electricity costs and reach the required load factor of the electrolyser.

3.3. Power-to-Liquid

Power-to-liquid (PtL), that is synthetic e-diesel produced from renewable hydrogen and CO_2 through the Fischer-Tropsch (FT) synthesis, could theoretically provide for a CO_2-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 well-established transport, distribution and refuelling infrastructure which could continue to be used. The key challenges are the high energy conversion losses during the fuel production process, the comparatively low thermal efficiency of the internal combustion engine, the resulting high renewable fuel costs, only limited air pollutant emission reductions and an increased exposure to energy imports from outside Europe due to a significantly increased renewable electricity demand.[x]

The FT synthesis requires renewable hydrogen and CO_2 from direct air-capture (DAC) as feedstock. DAC, i.e. capturing the CO_2 directly from the air, is the only viable method to produce a carbon-neutral fuel. Less costly carbon capture and utilisation (CCU) from an industrial point source would be significantly cheaper but risks double-counting and can not guarantee a closed CO_2 cycle, i.e. carbon-neutral production and combustion of the fuel.

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

In line with the assumptions for (OC)-BEVs and FCEVs, the tank-to-wheel energy demand of vehicles running on synthetic e-diesel (ICEVs_PtL) takes into consideration an optimistic, upper-bound estimate of energy efficiency improvements for diesel trucks that can be expected from the European CO_2 emission performance standards, i.e. a reduced fuel consumption of -21% by 2030 for tractor trailers against the 2019/2020 baseline based on Delgado et al. (29.86 L/100 km in 2020 and 23.47 L/100 km in 2030).[xi,66] This includes an increase in average brake thermal efficiency (BTE) of the engine from 42% in 2020 to 48% by 2030. In practice, this level of efficiency improvements would require an optimised, more aerodynamic tractor design.

3.4. Power-to-Methane

Power-to-methane (PtM), that is synthetic e-methane produced from renewable hydrogen and CO_2 from DAC, could also theoretically provide for a CO_2-neutral pathway to decarbonise long-haul road freight. The advantages of power-to-methane are the relatively mature vehicle technology and manageable engine adaptations which would be required. 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 an increased exposure to energy imports from outside Europe due to a significantly increased renewable electricity demand.[67]

Availability of sustainable biomethane

Biomethane, renewable methane upgraded from biogas, could theoretically be an effective instrument to reduce GHG emissions from the German HGV fleet. Whereas first-generation crop-based feedstocks should not be considered due to their high emissions from direct and indirect land use change and negative environmental impacts, advanced waste- and residue-based biomethane produced from anaerobic digestion and biomass gasification could indeed deliver strong GHG reductions if stringent sustainability criteria are applied. In 2020, a total of 0.9 TWh of biomethane was used in the German transport sector.[68]

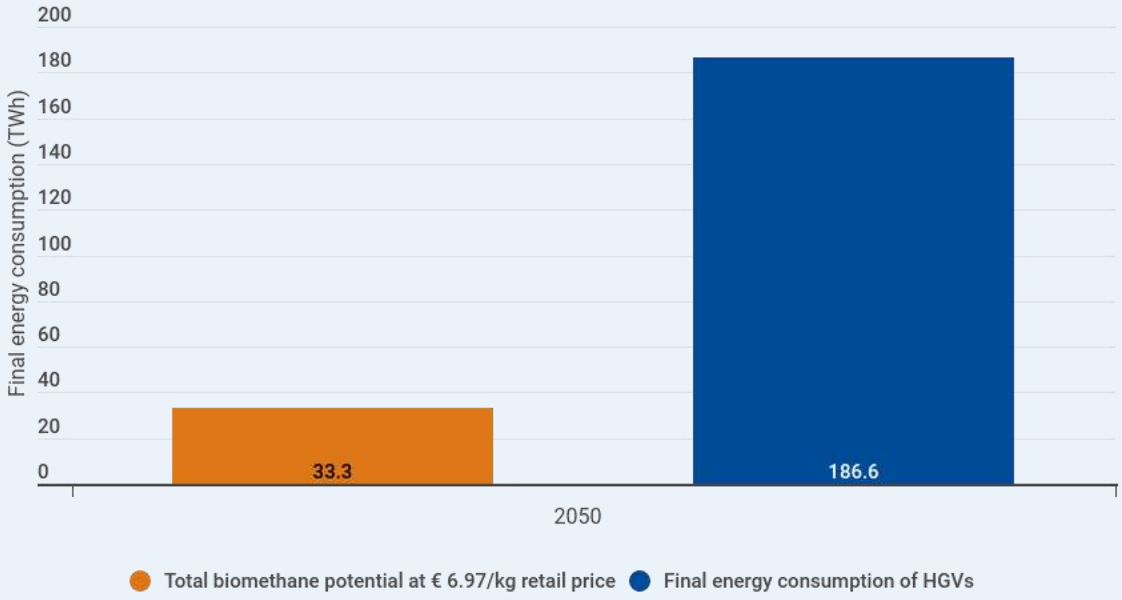
[xi] A reduction value of -21% seems an optimistic upper-bound estimate when considering that a share of the 2030 fleet reduction target (30%) will be achieved by the deployment of zero- and low-emission vehicles (ZLEVs). New sales of ZLEVs will effectively lower the nominal reduction target, both through their counting as multiple vehicles until 2025 as well as through the voluntary sales benchmark from 2025 onwards.

However, the availability of sustainable biomethane from advanced waste- and residue-based feedstocks is far too low to supply a larger share of the HGV fleet in Germany. Searle et al. estimated the maximum sustainable biomethane potential at different cost levels in Germany and concluded that only a low production level would meet the necessary sustainability criteria (see Figure 6).[69] Taking into account total lifecycle GHG emissions, Searle et al. 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 feedstock availability analysis, Germany could supply 33.3 TWh of biomethane per year in 2050 at a marginal retail price of € 6.97/kg_{CNG} disregarding additional liquefaction, transport, distribution and storage costs.[xii] This is more than six times the average retail price of compressed natural gas (CNG) as a transport fuel in Germany (between € 1.08 and 1.13/kg_{CNG} for high-calorific gas).[70,71] The 33.3 TWh production potential could only be realised with significant policy support: A subsidy level of almost € 6.00/kg would be necessary in order to reach price-parity with fossil methane. For comparison, the retail price of liquefied power-to-methane produced from renewables and imported from overseas could reach as low as € 2.48/kg_{LNG} in 2050 (see Section 5.2.1).

The final energy consumption, which would be required if Germany's whole HGV fleet was running on methane in 2050 would amount to 186.6 TWh after taking into account fuel efficiency improvements as well as modal shift to rail and waterborne freight. This means that if the entire sustainable biomethane potential in Germany was allocated exclusively to HGVs, it could meet a mere 18% of the fleet’s expected final energy consumption in 2050.

[xii] Germany-specific data for the feedstock potential was obtained from the authors of the study. It should be noted that the production cost of sustainable biomethane will be lower than € 5.54/kgCNG initially and that the marginal cost will increase incrementally for each additional feedstock potential which is used.



Notes: Comparing the final energy consumption of a dual-fual CI HPDI gas vehicle fleet with the total sustainable biomethane production potential in Germany. Assuming that all available biomethane is supplied to HGVs, leaving nothing for the power, industry or buildings sectors. Based on a biomethane retail price of € 6.79/kg, this is more than six times the average price level of compressed fossil methane (CNG) as a transport fuel in Germany.

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

Figure 6: 2050 sustainable biomethane potential vs. final energy consumption of HGVs

Profit margins in the haulage industry are low and fuel costs make up a large part of the total cost of ownership. If the entire sustainable biomethane potential was allocated to the road freight sector, nothing would be left for the power, industry or buildings sector. This would furthermore imply that current biomethane consumers would no longer be able to use it.

It is highly unlikely that any significant share of the available biomethane would be allocated to the German road freight sector when multiple sectors would be competing for it. Biomethane as a fuel for gas trucks is therefore not further considered in this study.

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 use as transport fuel. This means that the automotive fuel and combustion characteristics are identical.[72] The gaseous fuel can either be compressed or liquefied for storage purposes and combusted in a modified thermal engine to propel the vehicle. For the reason that long-haul HGVs require longer vehicle ranges, gas-powered tractor trailers need to store their onboard fuel in liquefied form (LNG).

The hydrocarbon-based gaseous fuel is produced through methanation (also called the Sabatier process). 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.

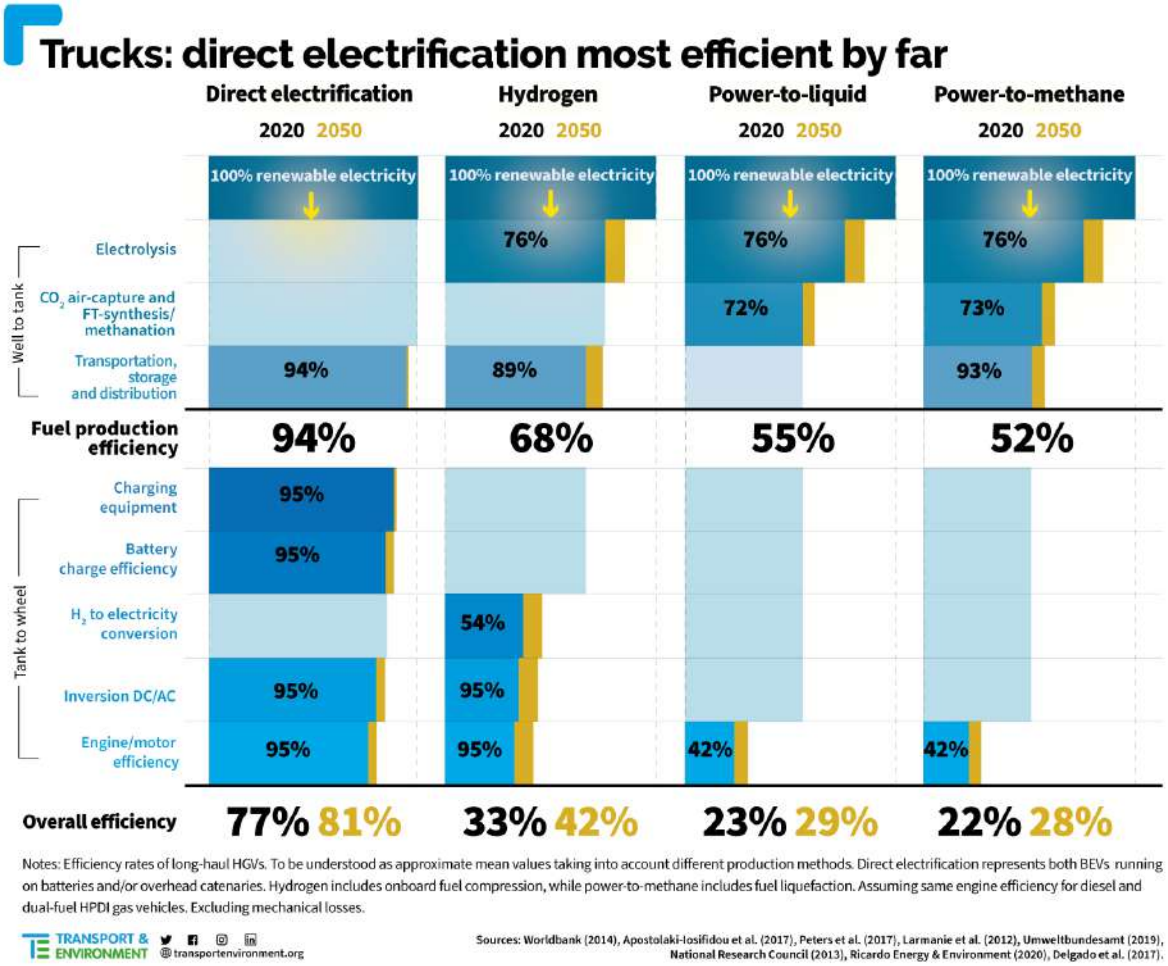
For the vehicle running on synthetic e-methane (ICEVs_PtM), a dual-fuel compressed ignition (CI) engine was chosen in combination with the high pressure direct injection (HPDI) technology which can achieve the same fuel efficiency as conventional diesel engines (2.96 kWh/km in 2020 and 2.33 kWh/km in 2030). This assumption is based on literature sources and manufacturer statements.[73] No additional energy losses due to boil-off or venting are considered. The dual-fuel engine is primarily powered by methane and uses smaller amounts of diesel as secondary fuel to ignite the fuel-air mix.[74] For simplification, the cost analysis assumes that these vehicles run on synthetic e-methane only

4. Renewable electricity demand

The different vehicle technologies are subject to different conversion efficiency losses and therefore need varying amounts of renewable electricity, either directly or indirectly as input for the production of renewable hydrogen or synthetic e-fuels. Figure 7 shows the average conversion efficiency rates based on todays and the maximum technical potential in 2050.[75,xiii] Direct electrification is and will remain at least twice as efficient as renewable hydrogen and around three times as efficient as internal combustion engines running on liquid or gaseous e-fuels.

[xiii] The conversion efficiencies serve illustrative purposes and are to be understood as approximate mean values taking into account different production pathways. The calculation of renewable electricity and fuel costs in the cost analysis is based on the conversion efficiencies of the Agora PtG/PtL calculator (well-to-tank) and the vehicle fuel consumption values (tank-to-wheel) which are listed in the Annex.

Trucks: direct electrification most efficient by far

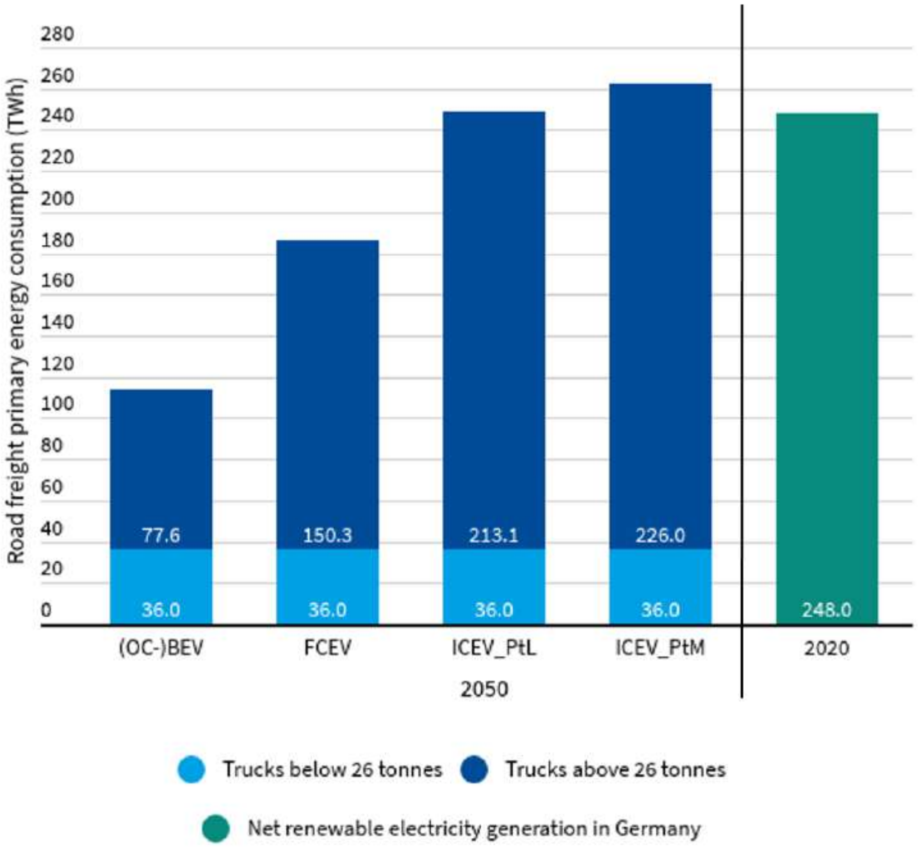


Notes: Efficiency rates of long-haul HGVs. To be understood as approximate mean values taking into account different production methods. Direct electrification represents both BEVs running on batteries and/or overhead catenaries. Hydrogen includes onboard fuel compression, while power-to-methane includes 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 7: Conversion efficiencies of the different vehicle technologies

This has an impact on the amount of additional renewable electricity needed for the different technology pathways. Figure 8 illustrates the additional renewable electricity demand and compares it to the 2020 net renewable electricity generation in Germany.[76] 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 GVW. In 2050, the direct electrification pathway would require an equivalent of 46% of Germany's 2020 net renewable electricity generation, the hydrogen pathway 75% and the two hydrocarbon pathways 100% and 106%.



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

Sources: T&E calculations and Fraunhofer ISE (2020).

Figure 8: 2050 primary energy consumption compared to 2020 net renewable electricity generation

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 Germany and Europe. Renewable electricity should therefore be used as efficiently as possible. Because the decarbonisation of the aviation and shipping sectors as well as other hard-to-abate sectors such as industry will rely on electricity-based fuels and renewable hydrogen in particular, direct electrification should take precedence in road transport wherever feasible.

Proponents of electricity-based fuels in road transport often refer to the need of temporary and seasonal energy storage in a fully renewables-based power system. It is, however, disputable, whether road transport should be used for such storage functions. There are likely more cost-effective options to balance and store renewable electricity which should be exploited first: additional interconnector capacities between EU countries, load levelling and peak shaving through cross-sectoral demand management, temporary stationary battery storage to balance daily surpluses and pumped storage facilities in Northern Europe for longer electricity storage needs. Renewable hydrogen imports will be used to balance seasonal renewables fluctuation by using it in gas peaker plants to generate electricity during, for example, winter times.[77]

5. Cost analysis

Renewable electricity costs are only one of the cost components which need to be considered. The system costs comprise all capital and operating costs for each vehicle technology taking into account its purchase, energy and infrastructure requirements. The user costs, or total cost of ownership (TCO), on the other hand describe the full purchase, ownership and operating costs after including all taxes, levies, charges and subsidies. Driver-related labour costs as well as insurance and vehicle financing costs are not included as they do not differ between the technologies.

5.1. System costs

Unlike a TCO, the system costs refer to the technology and production costs that need to be borne to a different degree by the manufacturers, operators, consumers and the public sector. They exclude all taxes, levies and charges except for grid connection fees as well as electricity network and distribution costs in order to allow for an undistorted assessment of the real costs and a fair comparison between direct electrification and electricity-based fuels.

5.1.1. Vehicle costs

The bottom-up vehicle cost estimates are based on Kühnel et al., Moultak et al., Meszler et al. and the U.S. Department of Energy and can be found in the Annex.[78,79] All vehicle technologies share the same characteristics which are required to meet the typical use profile of a long-haul tractor trailer used for commercial road haulage under type-approval legislation in the EU. The detailed vehicle specifications for the year 2025 are shown in Table 2.

Parameters	ICEV_diesel	BEV	OC-BEV	FCEV	ICEV_PtL	ICEV_PtM
Powertrain	Diesel engine (350 kW)	Electric motor (350 kW)		PEM fuel cell (240 kW) - Electric motor (350 kW)	Diesel engine (350 kW)	Dual-fuel CI HPDI engine (350 kW)
Energy storage	Diesel tank	Battery		Compressed H_2 fuel tank - Battery	Diesel tank	LNG tank - Diesel tank
Storage tank and nominal battery capacity in 2025	570 L_{diesel}	1,187 kWh	288 kWh	54 kg_{H2} - 127 kWh	570 L_{diesel}	205 kg_{LNG} - 170 L_{diesel}
Maximum range without refuelling and recharging	> 1,900 km	800 km	> 800 km - 200 km on battery	800 km[xiv]	> 1,900 km	1,058 km

Table 2: Vehicle specifications in 2025

The tractor trailer has a GVW of 40 tonnes, a curb weight of 14.4 tonnes which decreases to 12.1 tonnes until 2030 due to lightweighting, and a resulting maximum payload capacity of up to 25.6 tonnes (27.9 tonnes in 2030). Vehicle and component weight assumptions are based on Kühnel et al., Meszler et al., Sharpe, Wietschel et al. and Hall et al. The long-haul duty cycle examined in this study involves multi-day intercity travel with maximum daily trip lengths of up to 720 km if the vehicle is operated by one driver.

[xiv] Hydrogen trucks can be equipped with a larger storage tank to reach ranges of 1,200 km or more. A larger storage tank would also entail higher component costs. The assumed range of 800 km among the zero-emission vehicle options were therefore aligned to allow for comparability.

The average annual mileage over the first use period is assumed to be 136,750 km based on data from the TRACCS project which was funded by the European Commission.[80] This translates to an average daily mileage of 547 km based on 250 operating days per year.

The vehicle costs are kept constant after 2030 and until 2050 as it is not possible to make reasonable assumptions beyond this date. They take into account a first vehicle use period of five years and the remaining residual value of 24.9%. Vehicle components, which will need to be replaced after the first use period, are subtracted from the residual value. This is neither the case for the battery packs of the (OC-)BEV, which can last for 1.0 - 1.5 million km before they reach a critical level of retention (see Sections 3.1.1. and 3.1.2.) nor the fuel cell stack whose lifetime range should amount to around 1.4 million km according to the U.S. Department of Energy and Roland Berger.[81]

Kühnel et al. included a markup factor of 40% to determine the retail price after accounting for manufacturing, assembly and distribution costs as well as the manufacturer's profit margin. This mark-up factor was consistently applied to all vehicle components. The total net retail price (i.e. excluding vehicle taxes, VAT, insurance and financing costs) include the component costs due to the vehicle glider, tyres, conventional powertrain (internal combustion engine, exhaust aftertreatment system and diesel tank), electric axle (electric motor with a rated power output of 350 kW, inverter and gearbox), fuel cell system (Proton Exchange Membrane (PEM) fuel cell stack with a rated power output of 240 kW), hydrogen storage tank (compression at 700 bar), battery pack including a thermal management system, additional electric vehicle systems and the pantograph. Maintenance & repair 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 higher the scale of production, the lower the cost will be for a given vehicle component. Both battery packs as well as fuel cell systems and hydrogen storage tanks are assumed to use similar technology in heavy-duty applications as for the light-duty segment. Therefore, price projections for these component prices are assumed to converge (if they have not already done so), thereby allowing for the necessary economies of scale in heavy-duty applications.

The estimated vehicle costs are based on a hypothetical scenario where the manufacturing capacities and production lines are up and running and such vehicle components are mass-produced at larger scale. This should be kept in mind in the case of vehicle components which are currently not produced at larger scale neither for the light-duty nor heavy-duty vehicle market such as fuel cells and hydrogen storage tanks.

Prices of automotive batteries have fallen dramatically over the past years and are expected to decrease further. The retail battery pack prices are based on BloombergNEF's 2020 forecast for light-duty vehicles and include a mark-up of 40% as it was done for the vehicle components above to account for any additional material, manufacturing and distribution costs and any potential broader price range in the future. Battery pack prices have reached a volume-weighted industry average of € 112/kWh in 2020 and will likely decrease further towards at least € 47/kWh in 2030, mainly due to rapidly increasing production and greater economies of scale through the light-duty vehicle segment.[82] BloombergNEF's estimates are comparable to other battery pack cost curve projections.[83]

It is assumed that the currently existing cost gap between battery packs for passenger cars and heavy commercial vehicles is a temporary phenomenon due to lower scale of production on the heavy-duty side, and that the cost level will quickly converge once the production of electric trucks and buses ramps up in the coming years. This converging trend can be observed in the Chinese commercial vehicle market which has already reached greater scale of lithium iron phosphate (LFP) batteries, mostly through leverage from the electric bus market: BloombergNEF estimates that the 2020 volume-weighted average pack prices for commercial vehicles in China have reached as low as € 86/kWh, whereas they were still quite high at € 329/kWh in all other regions due to the lack of production scale.

It is reasonable to assume that pack prices for the light- and heavy-duty vehicle segment will converge by 2023 when electric truck production accelerates. However, batteries for long-haul trucks will require modified, higher-performance cell chemistries to enable longer ranges and higher energy density which may result in higher raw material costs. The included 40% mark-up factor takes this expected cost premium into account.

The specific energy density values are the low assumptions on the potential for future technological improvement based on Ricardo Energy & Environment.[84] A sensitivity analysis was undertaken to account for a scenario where battery pack costs decline faster throughout the decade than currently projected by BloombergNEF (see Annex for the results). The rapid ramp-up of production capacity and recent industry announcements by companies across the battery value chain indicate that this may turn out to be an upper-bound estimate after all.[85,86,87,88]

	2020	2025	2030
Battery pack costs incl. mark-up in €/kWh	248	101	66
Battery pack costs incl. mark-up in €/kWh (sensitivity)	248	96	46

Specific energy density at cell level in Wh/kg	235	314	408
Specific energy density at pack level in Wh/kg	183	245	318

In regards to fuel cell systems and hydrogen storage tanks, the estimated component costs are based on an annual production reaching 10,000 units in 2030 per manufacturer based on the U.S. Department of Energy, Moultak et al., Roland Berger and Hill et al. and take into account the mark-up factor which was used for all other vehicle components (if applicable).[89]

A sensitivity analysis was included with a higher annual production of fuel cells of 50,000 units per manufacturer in 2030 based on a 'catch-all scenario' with an extensive and swift market ramp-up of heavy-duty FCEV production in the second half of the 2020s (see Annex for the results).

	2020	**2025**	**2030**
Fuel cell system cost incl. mark-up in €/kW	811	309	155
Fuel cell system cost incl. mark-up in €/kW (sensitivity)	811	309	99
Hydrogen storage tank cost incl. mark-up in €/kWh	41	24	22
Hydrogen storage tank cost incl. mark-up in €/kWh (sensitivity)	41	14	11

It should be noted that European manufacturers are planning to begin series production of fuel cell electric trucks only from the second half of the 2020s.[90,91,92,93] The hydrogen industry has announced to deploy a total number of 10,000 hydrogen trucks by 2025 and 100,000 by 2030 in Europe.[94] These sales targets are in itself not sufficient to reach the sensitivity cost level assumed above. It is questionable whether a single truck manufacturer would be able to achieve an annual production level of 50,000 units in the second half of the decade when considering that a total of 274,000 new heavy-commercial vehicles above 16 tonnes GVW (excluding buses and coaches) were newly registered in the EU and EFTA in 2019.[95]

Bearing in mind that only a share of trucks above 16 tonnes would be hydrogen trucks and that an increase in new vehicle registrations due to increasing freight activity can be expected, none of the

European truck manufacturers alone would likely be able to reach a production scale of 50,000 units per year for the European market only.[96,xv]

A time penalty due to operational downtime is not considered since the BEV is charged in alignment with the EU driving times and rest periods without adverse impact on the operations. The net retail price for the BEV takes into account a payload penalty due to the additional vehicle weight and resulting payload loss until the second half of the 2020s. Since a proportion of vehicle trips are carried out only partially loaded or even empty, it is presumed that, in line with Hall et al., 50% of the vehicle fleet would be constrained by weight limitations. For comparison, Hill et al. estimate that the share of vkm performed by long-haul trucks above 32 tonnes GVW, which is constrained by weight limitations, is only between 10% and 19.5%, while the average loading factor was estimated to be around 56%.[97] This aligns well with data from the Department of Transport which estimated an average loading factor of 63% for long-haul trucks.[98]

5.1.2. Energy costs

The Agora PtG/PtL calculator was used to calculate the levelised cost of renewable electricity (LCOE), the levelised cost of renewable hydrogen (LCOH) and the cost of synthetic e-fuels produced from both.[99] It should be noted that all technology pathways are based on renewable electricity, whether in direct or indirect form. This explicitly includes direct electrification through the (OC-)BEV as well.[xvi]

Supplying all technologies with renewable-based energy has been a deliberate choice to ensure a fair comparison between those vehicle technologies which can achieve zero well-to-wheel GHG emissions, though not lifecycle GHG emissions. This means that emissions incurred from the construction and dismantling of electricity and fuel production facilities are not taken into account.[100] Likewise, any potential time- or space-related deployment limitations are disregarded. The detailed energy costs can be found in the Annex.

[xv] Leveraging light-duty vehicle production volumes to achieve the necessary economies of scale is, at this stage, no longer foreseeable. To reduce costs by increasing the utilisation of their production lines and serving multiple regional markets at once, truck manufacturers may pursue partnerships and try to serve other markets such as maritime shipping or stationary back-up applications where fuel cells will play a major role.

[xvi] In practice, hauliers and charging infrastructure operators will either use grid electricity to charge the vehicles, or conclude a PPA under which they agree to purchase renewable electricity directly from a utility company (or a combination of both).

The electricity generation and fuel production facilities are based on offshore wind in the North Sea with connection to Germany's electricity grid and domestic fuel production plants located near the German coast. A sensitivity analysis was undertaken based on solar PV in North Africa for electricity-based fuels considering that the MENA region represents a particularly favourable location to produce renewable hydrogen and synthetic e-fuels more cheaply due to lower renewable electricity costs.

The cost calculations are based on the reference scenario of the Agora PtG/PtL calculator.[101] The weighted average cost of capital (WACC) was set at 6% and DAC was chosen as the CO_2-extraction method. Offshore wind in the North Sea was set at a load factor of 4,000 full-load hours per year. Likewise, low-temperature electrolysis as well as FT-synthesis and methanation operate at 4,000 full-load hours. For the sensitivity analysis, solar PV in North Africa as well as low-temperature electrolysis was set at 2,344 full-load hours, whereas both FT-synthesis and methanation were set at 4,000 full-load hours and, consequently, rely on temporary stationary hydrogen storage.

Grid connection fees are included in the LCOE for the direct electrification pathway. In addition, it includes electricity grid connection and network tariffs which are to be understood as the equivalent to the transport and distribution costs of electricity-based fuels. Electricity grid and network tariffs for non-households with an annual consumption between 500 and 2,000 MWh are based on Destatis.[102]

If the electricity-based fuels are produced overseas, they include costs due to liquefaction (if applicable), their subsequent transport via tanker vessel from North Africa (Port Said) to Germany (Port of Wilhelmshaven) and domestic distribution to the refuelling station via insulated cryogenic tanker trucks (renewable hydrogen) or conventional tanker trucks (synthetic e-diesel and e-methane). Other hydrogen carriers such as ammonia or LOHC are not further considered as they would likely be at least as expensive as liquefied hydrogen when taking into account reconversion.[103] Based on the plans of the European gas industry, it is assumed that a continuous hydrogen pipeline network will not emerge before the 2040s.[104] It is therefore expected that, if the renewable hydrogen is to be produced in Europe, decentralised production on-site at the refuelling station in combination with a PPA will likely represent the cheapest production pathway in 2030 due to the lack of transport and distribution costs (see also Figure 13).

Fuel processing (compression or liquefaction), transport and distribution costs are based on the U.S. Department of Energy, Hydrogen Council, Runge et al., Pfennig et al., Mottschall et al., Agora Verkehrswende et al., Fasihi et al. and Bünger et al. (see also the Annex).[105,106,107,108,109,110,111] The fossil diesel pathway includes the ten-year average diesel wholesale cost between 2010 and 2020 of €-cent 52.98/L in Germany (excluding fuel duty and VAT) which is kept constant over time.[112]

5.1.3. Infrastructure costs

The estimated infrastructure costs are based on Kühnel et al. They take into account the capacity and power of the refuelling and charging stations, utilisation rates, service life, capital expenditure, operational expenses and the number of supplied vehicles per station. A sensitivity analysis was undertaken for the OC-BEV to take into account a scenario with a lower utilisation rate of the overhead catenary infrastructure. This would have a substantial effect on the system and user costs (see Annex for the results).

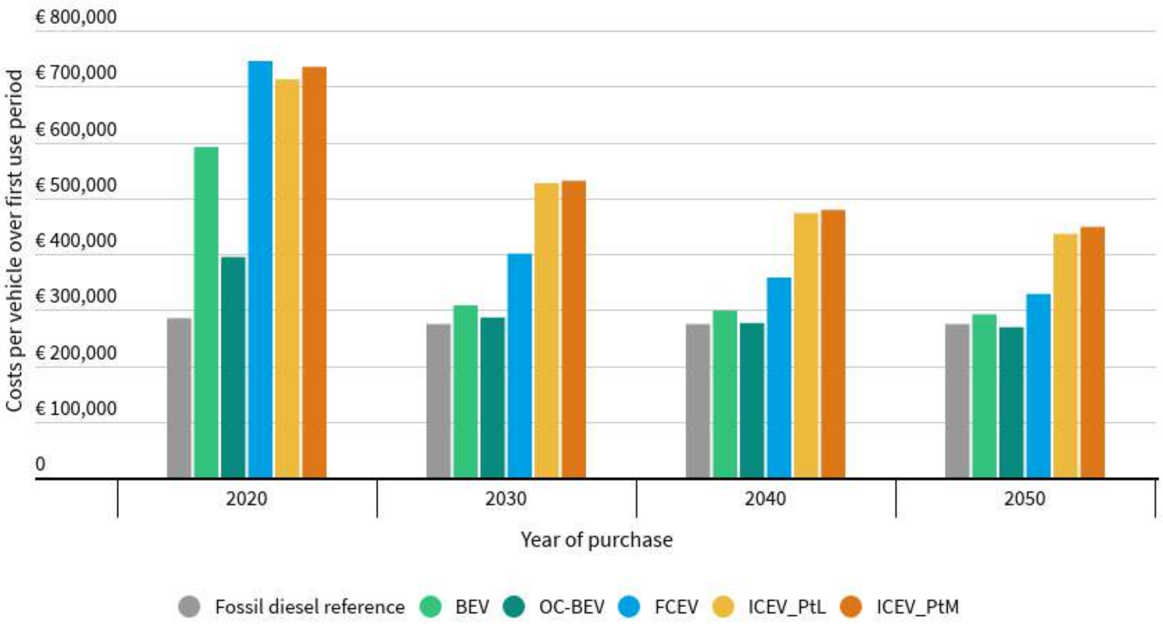
It should be noted that refuelling and charging cost estimates are to an extent speculative as the technologies are not yet fully commercialised, let alone scaled up on the market. The costs for both the recharging and refuelling stations follow similar cost reduction curves until 2030 and are kept constant afterwards. The costs for LNG refuelling stations are assumed to not decrease further because the technology is already commercialised and widely deployed. The detailed costs can be found in the Annex.

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

5.1.4. Results

The lifetime system costs of the vehicles are shown in Figures 9 - 12 and include the reference fossil diesel truck to allow for comparison. As mentioned, the system cost approach illustrates the true techno-economic costs of the different technology pathways and should not be confused with the TCO whose additional cost components in the form of taxes, levies, charges and subsidies will follow in the subsequent section.

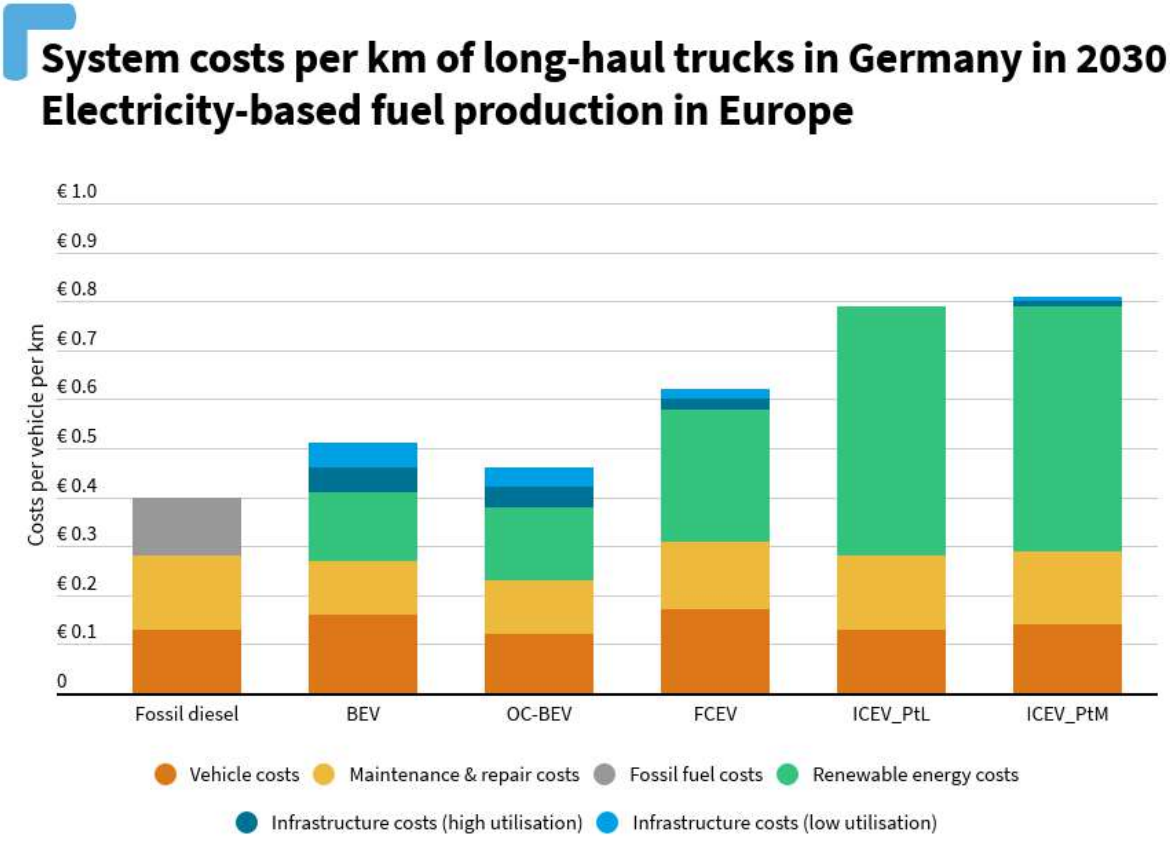
It should be noted that the technology costs due to vehicles and infrastructure are kept constant after 2030 and until 2050 as it is not possible to make reasonable assumptions beyond this date. That means that any reduction in costs beyond 2030 is solely due to decreasing renewable electricity and electricity-based fuel costs. In reality, further incremental cost reductions, especially in regards to the main vehicle components such as batteries, fuel cells and hydrogen storage tanks, can be expected depending on how the scale of production will evolve over time and how many market segments will be served by the different vehicle technologies.



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

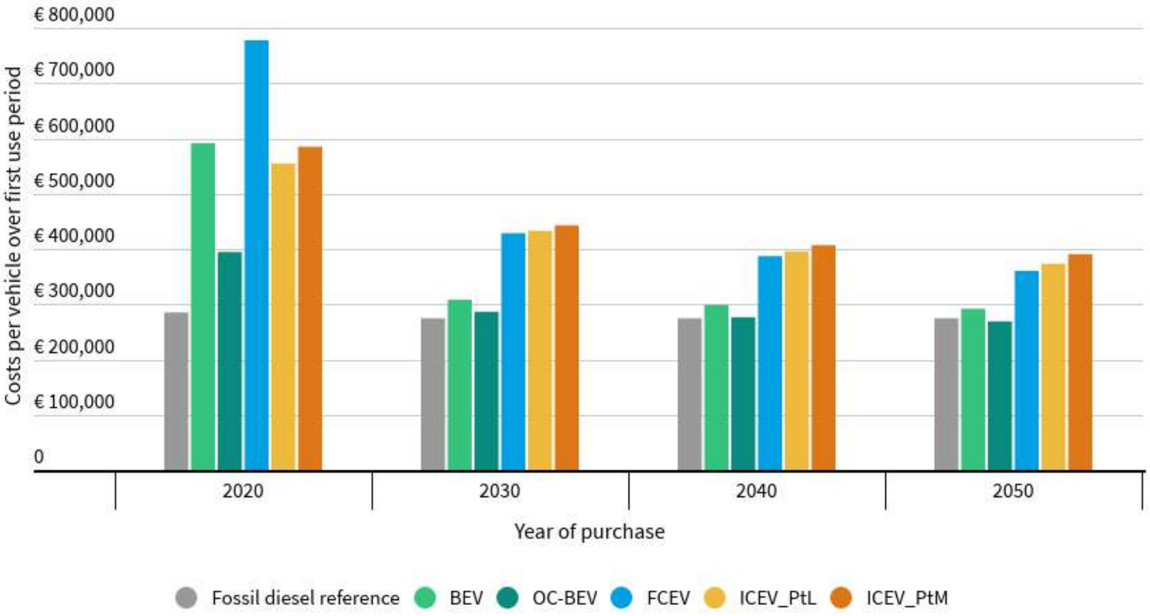
Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including vehicle costs (purchase costs, maintenance & repairs and residual value), renewable electricity and fuel costs and infrastructure costs (at high utilisation). Excluding taxes, levies and road charges except for grid connection fees and electricity transmission and distribution costs. BEV includes opportunity costs due to additional battery weight before 2030.

Figure 9: Lifetime system costs - base case with electricity-based fuel production in Europe


System costs per km of long-haul trucks in Germany in 2030
Electricity-based fuel production in Europe

Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including vehicle costs (purchase costs, maintenance & repairs and residual value), renewable electricity and fuel costs and infrastructure costs (at high utilisation). Excluding taxes, levies and road charges except for grid connection fees and electricity transmission and distribution costs.

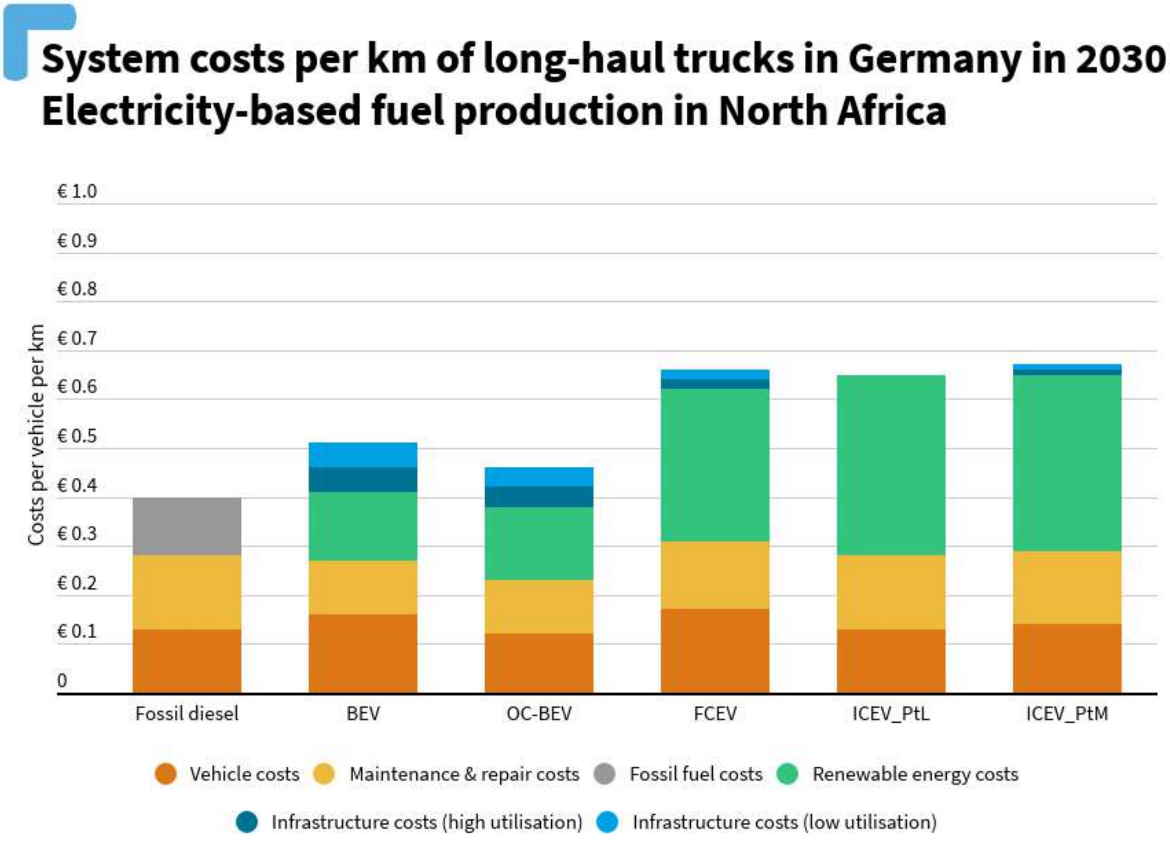
Figure 10: System costs per km in 2030 - base case with electricity-based fuel production in Europe



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

Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including vehicle costs (purchase costs, maintenance & repairs and residual value), renewable electricity and fuel costs and infrastructure costs (at high utilisation). Excluding taxes, levies and road charges except for grid connection fees and electricity transmission and distribution costs. BEV includes opportunity costs due to additional battery weight before 2030.

Figure 11: Lifetime system costs - sensitivity analysis with electricity-based fuel production in North Africa


System costs per km of long-haul trucks in Germany in 2030
Electricity-based fuel production in North Africa

Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including vehicle costs (purchase costs, maintenance & repairs and residual value), renewable electricity and fuel costs and infrastructure costs (at high utilisation). Excluding taxes, levies and road charges except for grid connection fees and electricity transmission and distribution costs.

Figure 12: System costs per km in 2030 - sensitivity analysis with electricity-based fuel production in North Africa

The results indicate that BEVs and OC-BEVs will likely represent the most cost-effective option amongst all technology pathways which can achieve zero well-to-wheel emissions when disregarding taxes, levies, chargers and subsidies. BEVs and OC-BEVs would likely also be cheaper than FCEVs running on renewable hydrogen and ICEVs running on synthetic e-fuels if those electricity-based fuels are produced overseas under ideal conditions and shipped to Germany. In the case of renewable hydrogen imports from overseas, higher processing, transport and distribution costs offset the lower production costs. Imported hydrogen only becomes cheaper than on-site production at the refuelling station when all taxes and levies are factored in (see Figure 13).

5.2. Total cost of ownership

The total cost of ownership (TCO) comprises the system costs and, in addition, all taxes and levies on the purchase, operation and refuelling of the vehicle as well as road charges and subsidies. In this sense, the TCO describes the total costs for the operator to own and operate the vehicle based on the given regulatory framework and taxation structure.

5.2.1. Taxes and levies

As explained above, the system costs already include grid connection fees for the renewable electricity generation facilities as well as costs due to transport and distribution (i.e. transmission and network) infrastructure for both electricity and electricity-based fuels. In addition, the TCO includes all taxes and levies (excluding VAT) on the purchase, operation and refuelling of the vehicle. Electricity-based fuels are taxed in accordance with the current legislative situation in Germany.

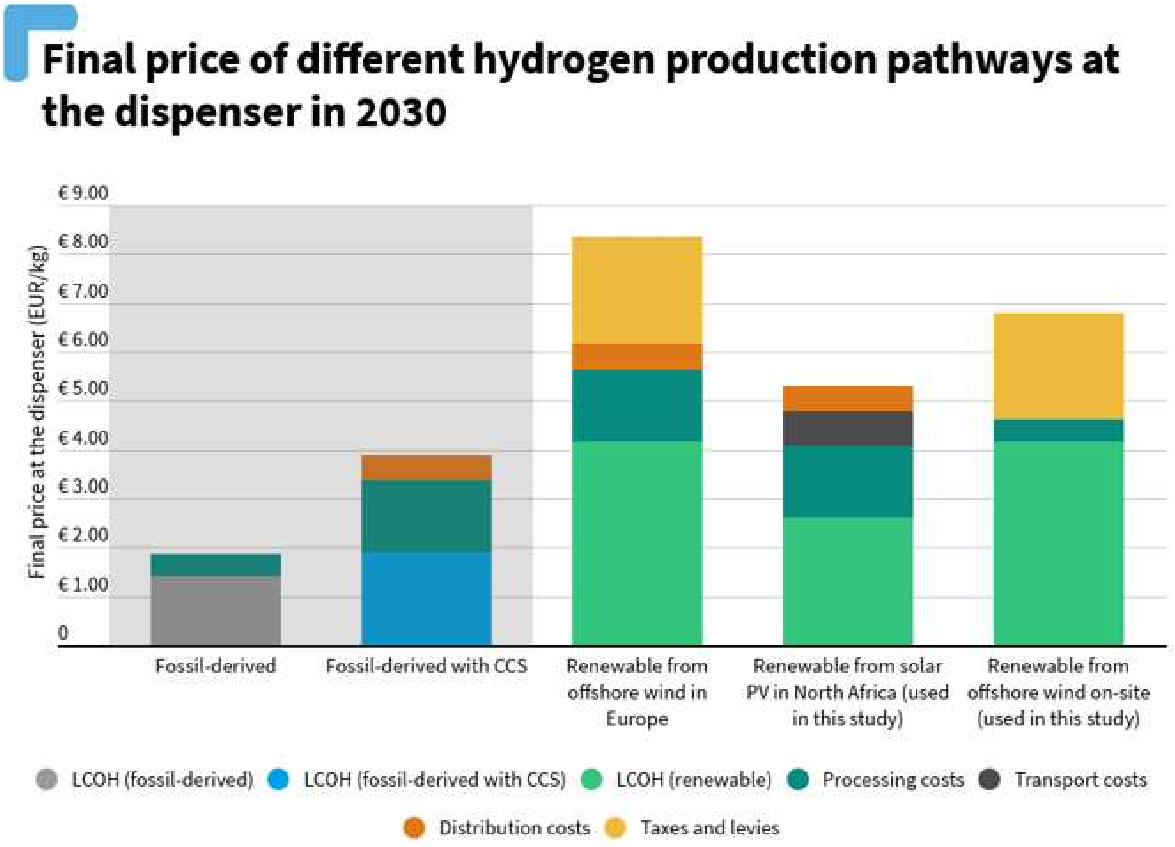
Vehicle taxes include the one-time registration charge ('Zulassungssteuer') of € 26.30 and the annual tax on the use of the vehicle ('Kraftfahrzeugsteuer') of € 556 per year.[113,114]

Besides grid and network tariffs for non-households which are already included in the system costs, the renewable electricity price includes the renewables levy ('EEG-Umlage') as well as further charges and levies and the electricity tax.[115] As mentioned above, an annual electricity demand between 500 and 2,000 MWh per consumer was assumed. This corresponds roughly to the annual electricity consumption of a long-haul truck fleet of 2 - 10 vehicles. For comparison, 65% of all haulage companies in Germany operate a truck fleet of 2 vehicles or more.[116] Resulting in a final renewable electricity price for non-households of €-cent 26.07/kWh in 2020, this is somewhat higher than the equivalent grid electricity price for non-households of €-cent 19.89/kWh for the same consumption band.[117]

Hydrogen used as a transport fuel is currently exempt from excise duty in Germany. This subsidy is maintained. Renewable electricity used by electrolysers is furthermore exempt from network tariffs and the renewables levy.[118,119] After accounting for processing (i.e. compression or liquefaction), transport and distribution costs as well as applicable taxes and levies on the electricity input, the final renewable hydrogen price at the dispenser ranges from € 5.30 to 6.79/kg in 2030. This compares to an estimated final fossil-derived hydrogen price at the dispenser of € 1.86/kg without carbon capture and storage

(CCS) and € 3.90/kg with CCS in 2020.[120,xvii] The detailed cost components of the different production pathways are illustrated in Figure 13 and compare well to other cost scenarios and assumptions from the literature.[121,122,123,124,125,126]

[xvii] The fossil-derived levelised hydrogen costs by the IEA represent a European average. It is assumed that fossil-derived hydrogen is produced at a centralised location in the Netherlands with subsequent CO_2 storage in depleted offshore gas fields along the Dutch continental shelf. The final cost at the dispenser therefore includes additional costs due to liquefaction and distribution to Germany.



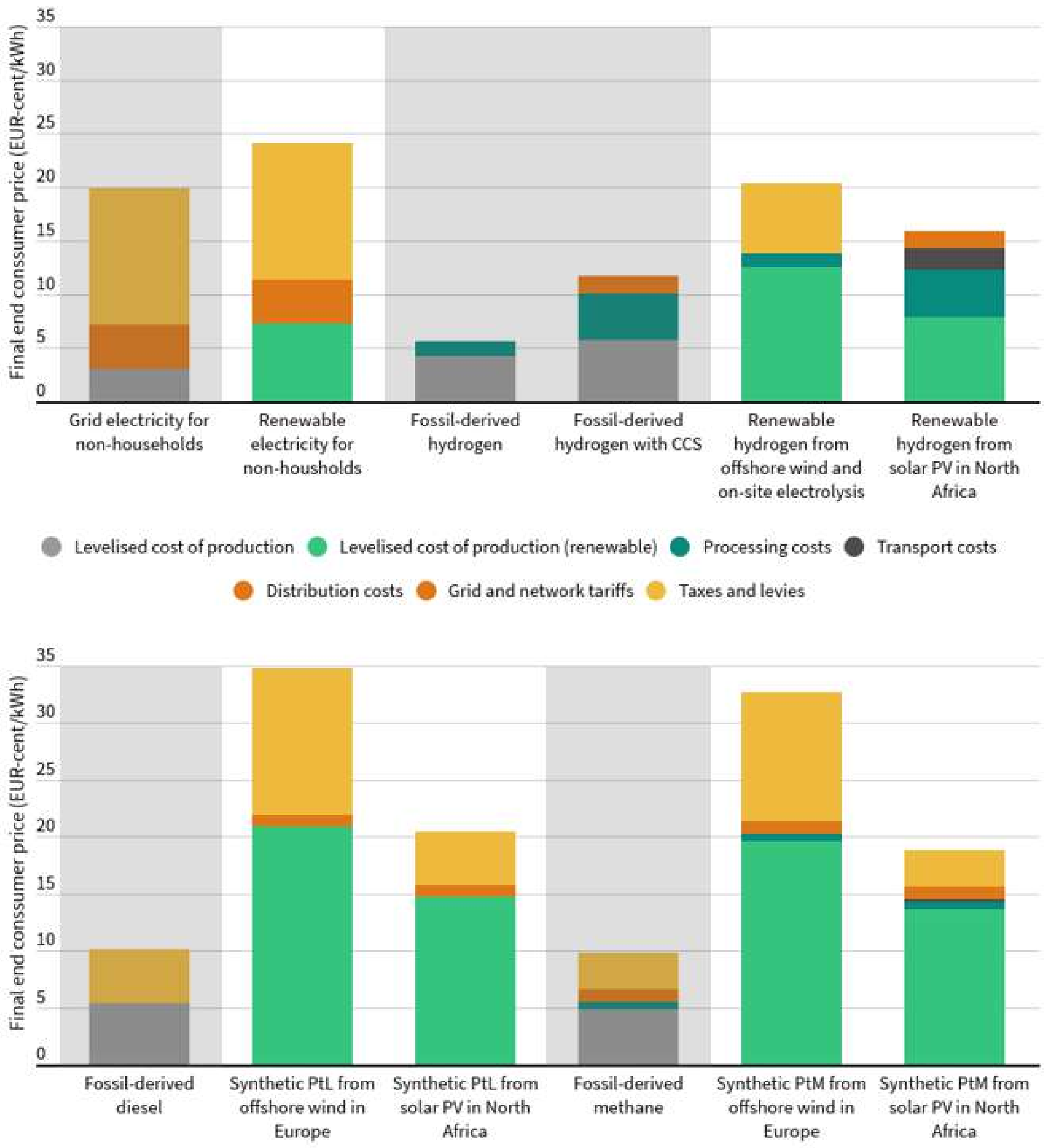
Notes: Fossil-derived hydrogen production from natural gas steam-methane reforming decentralised on-site. Fossil-derived hydrogen production with CCS centralised in the Netherlands with undersea storage in depleted North Sea gas fields. Processing costs are due conversion via compression or liquefaction. Transport costs refer to shipping from North Africa to Germany via cryogenic tanker vessel. Distribution costs refer to delivery via cryogenic tanker truck. In Germany, renewable hydrogen production is exempt from the renewables levy ('EEG-Umlage) and network tariffs ('Netzentgelte'); all other taxes and levies on electricity input apply. Hydrogen as a transport fuel is exempt from fuel duty.

Figure 13: Final price of different hydrogen production pathways at the dispenser in 2030

For the fossil diesel as well as the power-to-liquid pathway, the diesel fuel duty rate ('Energiesteuer') of €-cent 47.04/L is included and kept constant over time without inflation adjustment.[127] It is expected that transport operators will receive a compensation for the additional fuel costs which will be levied through the Fuel Emissions Trading Act ('Brennstoffemissionshandelsgesetz', or BEHG). Such a reimbursement system will likely be introduced as part of a revised 'Lkw-Maut' once its infrastructure charge is varied based on CO_2 and CO_2 is levied through an external cost charge. The price of € 25/tCO_2 in 2021 and which will increase to € 55/tCO_2 by 2025, is therefore not further taken into account.

For the power-to-methane pathway, the currently reduced fuel duty rate for natural gas used as transport fuel of €-cent 13.90/MWh is included, which will increase to €-cent 22.85/MWh by 2025 and eventually reach the normal rate of €-cent 30.80/MWh by 2027.[128]

Final electricity and electricity-based fuel prices in 2030



Notes: Electricity wholesale prices, network tarrifs, taxes and levies for non-household users with an annual consumption of 500 - 2,000 MWh. Fossil-derived hydrogen production from natural gas steam-methane reforming decentralised on-site. Fossil-derived hydrogen production with CCS centralised in the Netherlands with undersea storage in depleted North Sea gas fields. Processing costs are due conversion via compression or liquefaction. Transport costs refer to shipping from North Africa to Gerrmany via tanker vessel. Distribution costs refer to delivery via tanker truck. In Germany, production of renewable hydrogen and its derivatives is exempt from the renewables levy ('EEG-Umlage) and network tariffs ('Netzentgelte'); all other taxes and levies on electricity input apply. Hydrogen as a transport fuel is exempt from fuel duty.

Figure 14: Final electricity and electricity-based fuel prices in 2030

5.2.2. Road charges

Germany has a distance-based road charging scheme in place which currently comprises an infrastructure charge based on vehicle weight and number of axles as well as external cost charges for air and noise pollution.[129] Zero-emission vehicles are currently fully exempt from all road charge components.

The Eurovignette Directive, which lays out the rules and procedures that Member States have to follow when charging trucks for their infrastructure usage, is currently being revised in interinstitutional negotiations ('trilogues'). Under the Council's General Approach, Member States will have to vary the infrastructure charge for trucks based on their emission performance from 2023. For this, ICEVs and Z(L)EVs will be allocated to five CO_2 emission classes based on their performance against the linear emission reduction trajectory defined in the CO_2 standards for new HDVs.[130] Member States will also be permitted to keep full exemptions for ZEVs on the infrastructure charge until the end of 2025, after which the reduction must amount to 50 - 75% compared to less fuel-efficient ICE trucks in emission class 1. Member States would also have the option to apply a CO_2-based external cost charge as an alternative to varying the infrastructure charge, or to combine both instruments.[131]

As things currently stand, Germany intends to introduce CO_2-variation of the infrastructure charge in combination with an effective CO_2 external cost charge from 2023.[132] For ZEVs, it is therefore assumed that Germany would keep the current full exemption from the infrastructure charge until 2025, after which it has to be reduced to 75% compared to ICEVs in emission class 1. The conventional diesel truck is expected to benefit from a fuel efficiency improvement of around 21% between 2019/20 and 2030 (see Section 3.3.) and will therefore be allocated to emission class 1. The ICEV_PtM is assumed to be allocated to emission class 3 based on the expected emission performance of dual-fuel CI HPDI gas trucks. The current infrastructure and external cost rates are kept constant over time.

The resulting charges on the tolled network for the different vehicles are listed in the Annex. In line with Kühnel et al., it was assumed that long-haul tractor trailers perform 90% of their total mileage on the tolled road network which includes motorways and federal highways in Germany.

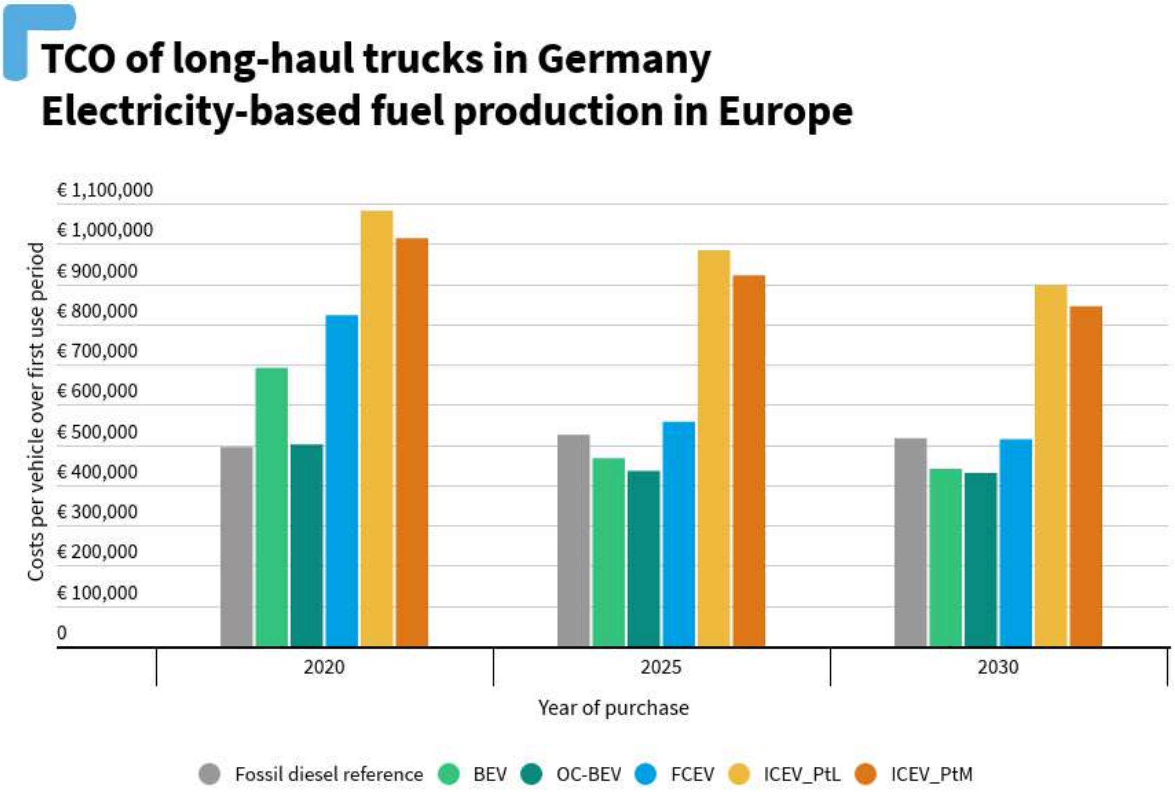
5.2.3. Purchase subsidy

In Germany, transport companies can receive grants of up to € 40,000 per zero-emission truck, whereby a maximum 40% of the additional vehicle investment costs are covered and the maximum amount a single company can receive is capped at € 500,000.[133] Gas trucks have been excluded from the programme since January 2021.[134,xviii] It is assumed that this subsidy will expire by 2026.

5.2.4. Results

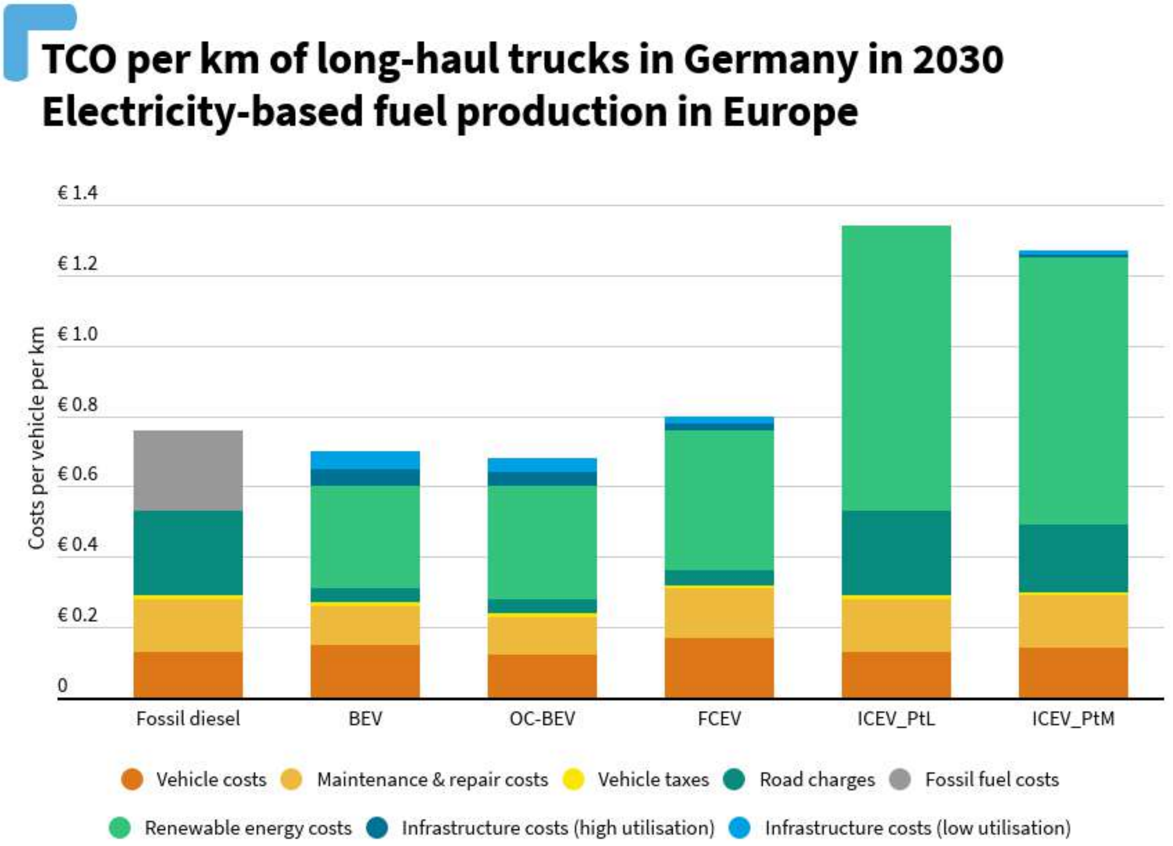
The results for the vehicle's first use period including all taxes, levies, charges and subsidies as they are currently legislated are shown in Figures 15 - 18 and include the fossil diesel reference to allow for comparison.

[xviii] A new programme with revised funding rates is expected to be adopted in early 2021.



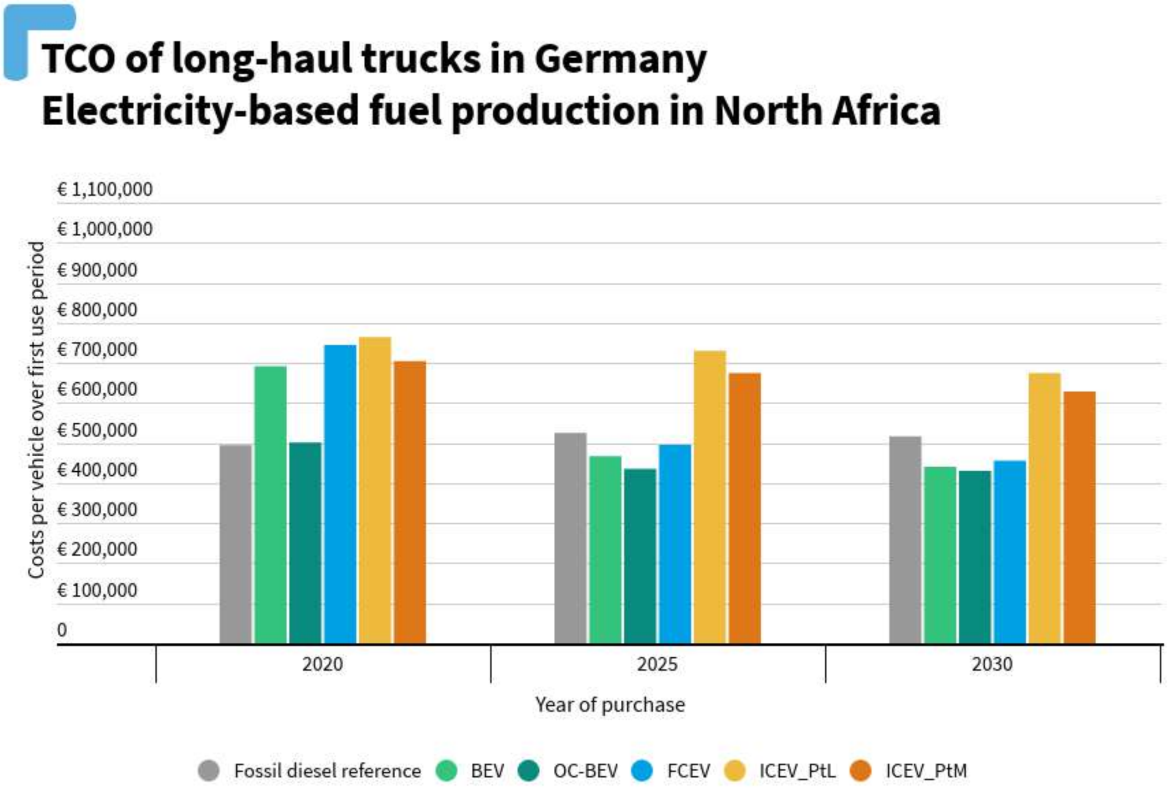
Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including total vehicle costs (purchase costs and residual value, maintenance & repairs, vehicle taxes, excl. financing costs and VAT), renewable electricity and fuel costs (incl. grid connection fees, transport and distribution costs as well as taxes and levies), infrastructure costs (at high utilisation) and road charges varied based on the Eurovignette Revision. BEV includes opportunity costs due to additional battery weight until 2025.

Figure 15: TCO - base case with electricity-based fuel production in Europe


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

Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including total vehicle costs (purchase costs and residual value, maintenance & repairs, vehicle taxes, excl. financing costs and VAT), renewable electricity and fuel costs (incl. grid connection fees, transport and distribution costs as well as taxes and levies), infrastructure costs (at high utilisation) and road charges varied based on the Eurovignette Revision.

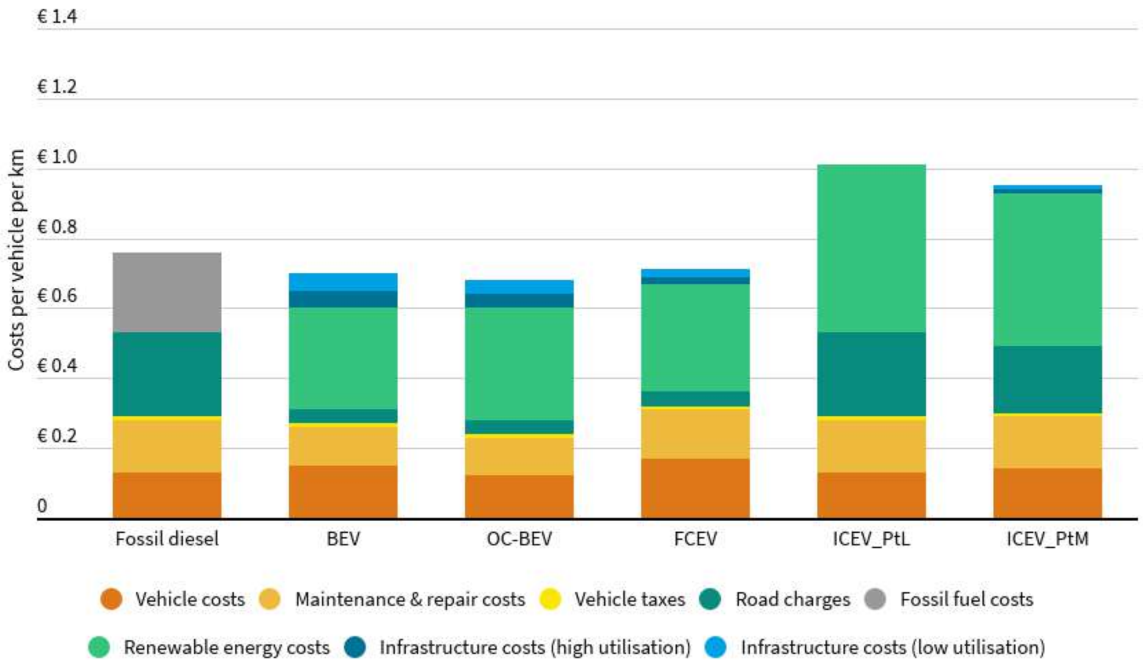
Figure 16: TCO per km in 2030 - base case with electricity-based fuel production in Europe



TCO of long-haul trucks in Germany Electricity-based fuel production in North Africa

Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including total vehicle costs (purchase costs and residual value, maintenance & repairs, vehicle taxes, excl. financing costs and VAT), renewable electricity and fuel costs (incl. grid connection fees, transport and distribution costs as well as taxes and levies), infrastructure costs (at high utilisation) and road charges varied based on the Eurovignette Revision. BEV includes opportunity costs due to additional battery weight until 2025.

Figure 17: TCO - sensitivity analysis with electricity-based fuel production in North Africa



TCO per km of long-haul trucks in Germany in 2030
Electricity-based fuel production in North Africa

Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including total vehicle costs (purchase costs and residual value, maintenance & repairs, vehicle taxes, excl. financing costs and VAT), renewable electricity and fuel costs (incl. grid connection fees, transport and distribution costs as well as taxes and levies), infrastructure costs (at high utilisation) and road charges varied based on the Eurovignette Revision.

Figure 18: TCO per km in 2030 - sensitivity analysis with electricity-based fuel production in North Africa

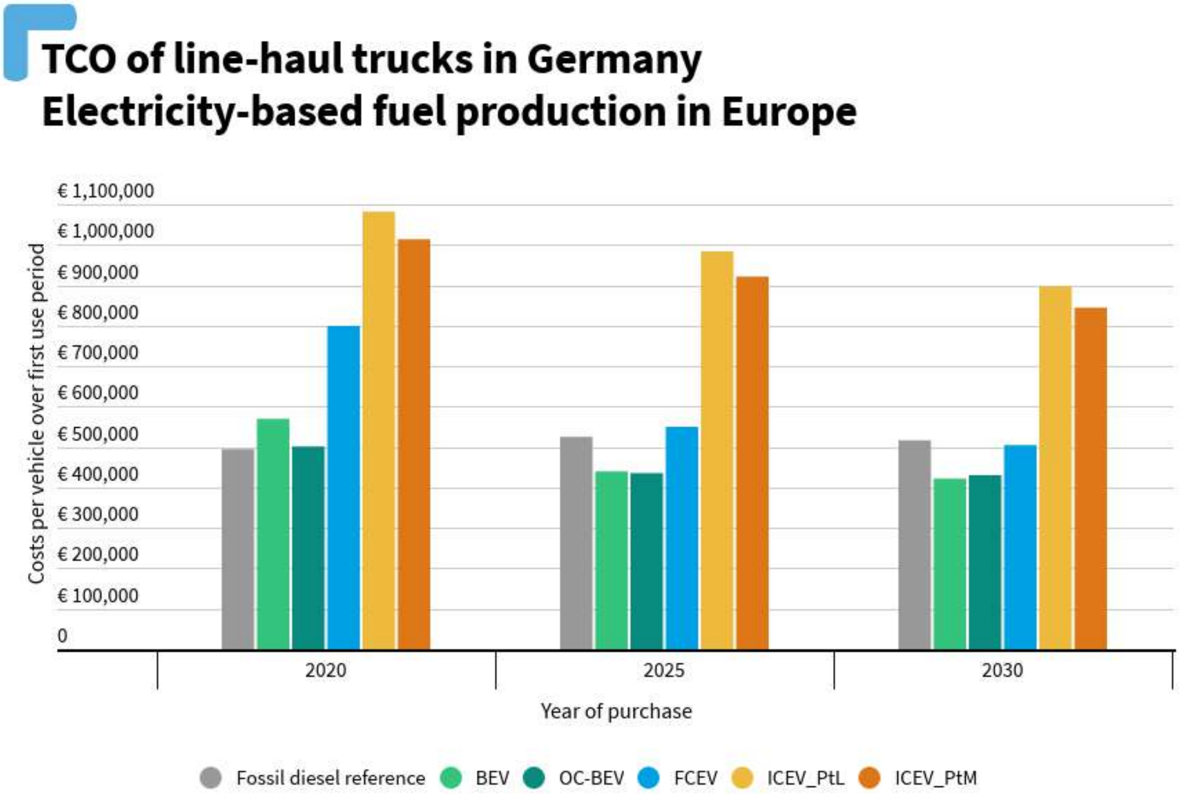
6. Discussion and outlook

Also when accounting for all taxes, levies, road charges and current subsidies, long-haul BEVs and OC-BEVs will likely represent the most cost-effective option in most scenarios. With the current purchase subsidy and a revised road charging scheme, long-haul OC-BEVs could reach TCO parity with fossil diesel trucks before the mid 2020s, BEVs in the mid 2020s and FCEVs around 2030. Long-haul BEVs and

OC-BEVs would also likely be cheaper than FCEVs and ICEVs running on electricity-based fuels when those are produced in North Africa under ideal conditions and shipped to Germany.

Road freight is a business and transport operators will opt for the most cost-competitive vehicle technology provided that it offers sufficient operational flexibility and can use a dense and reliable infrastructure network. It is highly unlikely that hauliers would be willing to pay an additional premium for technologies which offer a significantly higher vehicle range if their real-world operational profile actually does not require it. On the contrary, it should be expected that hauliers will opt for a shorter vehicle range if it meets their route and flexibility requirements in order to reduce costs.

For this purpose, it is worth examining a TCO of a line-haul truck with a 500 km range which would still be capable of covering around 60% of the road freight activity in Germany without the need to recharge or refuel in between. The cost advantage of the BEV due to the smaller onboard battery then becomes apparent (see Figure 19). Long-haul BEVs with a 500 km range are expected to enter the market in the coming years.

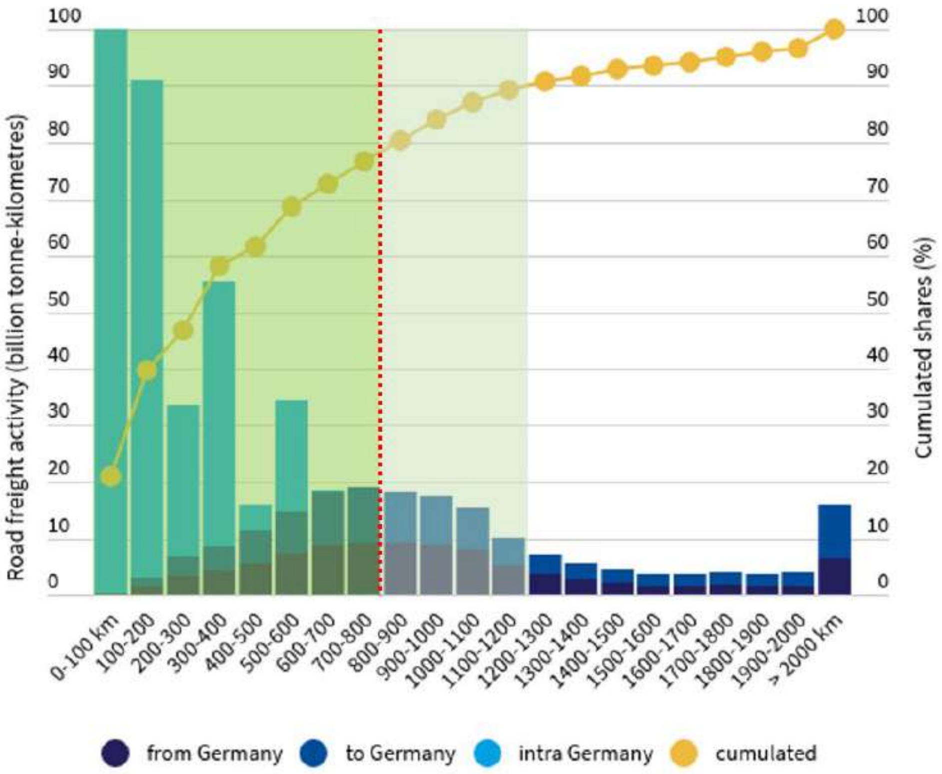


TCO of line-haul trucks in Germany
Electricity-based fuel production in Europe

Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 500 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including total vehicle costs (purchase costs and residual value, maintenance & repairs, vehicle taxes, excl. financing costs and VAT), renewable electricity and fuel costs (incl. grid connection fees, transport and distribution costs as well as taxes and levies), infrastructure costs (at high utilisation) and road charges varied based on the Eurovignette Revision. BEV includes opportunity costs due to additional battery weight until 2025.

Figure 19: TCO - base case for line-haul trucks with 500 km range

If vehicles with an 800 km range are equipped with one driver they can drive a maximum daily distance of 720 km per day due to the EU driving times and rest periods which also ensures a 10% safety margin for reaching the next charging location. Charging these trucks during the driver's rest period will extend their range to as much as 1,200 km which would cover close to 90% of the road freight activity measured in tonne-kilometres in Germany (see Figure 20).



Notes: Distribution of road freight activity across vehicle trip distance bands in Germany. Trips can last multiple days. The dark green shade illustrates the activity which can be covered by vehicles with 800 km range without recharging or refuelling. The light green shade extends this coverage based on one recharging or refuelling event during the mandatory daily rest period.

Sources: T&E calculations based on ETISplus (2010) and calibrated based on Eurostat (2018).

Figure 20: Road freight activity covered by BEVs with 800 km range if charged during the daily rest period

Hydrogen fuel cell trucks with longer ranges may be better suited for trip distances above 1,200 km. However, these trips only make up 11% of total road freight activity in Germany. There might also be other niche applications where hydrogen trucks may benefit from range- or cost-related advantages. For example, off-road vehicles such as dump trucks for mining operations may need longer ranges due to their exceptional operational uptime requirements. Likewise, vehicles for heavy-load and special road freight movements may need larger onboard energy storage as a result of specific operational needs, such as range or higher energy consumption. Remote areas which lack the necessary grid infrastructure for high-power charging could be another possible application scenario for FCEVs.

Hydrogen trucks could also have an operational and cost advantage for drayage applications in and around sea ports and their adjacent economic hinterland since container swaps are characterised by short pick-up times and because they would benefit from synergy effects with maritime shipping and lower fuel costs due to the future role of sea ports as hydrogen import terminals.

Ultimately, the economic cost-competitiveness of each vehicle technology will depend on how their economies of scale will evolve over the coming decade. Automotive batteries are currently experiencing a self-reinforcing dynamic which will drive down their costs dramatically due to the accelerating ramp-up in the passenger car market and this is soon expected to spill over to the urban and regional delivery truck segment and, subsequently, to long-haul trucking.

Dropping battery prices are expected to increasingly offset the relative cost advantages of OC-BEVs over the next few years. Fuel cells and hydrogen storage tanks will likely not see substantial cost reductions due to the lack of larger scale before the second half of the 2020s. Other potential fuel cell markets such as maritime shipping or stationary back-up applications will likely not scale up to any critical extent before the 2030s. This will likely make it extremely challenging for hydrogen trucks to attain any sizable market share in the heavy-goods vehicle segment.

7. Policy recommendations

Road haulage is a business which means that it will require both strong regulation and substantial incentives so that zero-emission alternatives can reach cost parity with conventional diesel trucks. The Federal Government should focus on more stringent regulation both at national and EU-level as well as targeted funding incentives for zero-emission trucks and infrastructure.

7.1. Demand for zero-emission trucks

ZEV purchase grant

Initially higher upfront purchase costs of ZEVs are a significant barrier for hauliers, notably small- and medium enterprises. In order to incentivise initial demand and accelerate the market uptake, purchase subsidies are needed for a limited period of time. Grants should not be made available for gas-powered trucks as biomethane supply cannot scale to supply a significant share of the HGV fleet.

In Germany, transport companies can receive grants of up to € 12,000 (GVW up to 12 tonnes) and € 40,000 (above 12 tonnes) for zero-emission trucks, whereby a maximum 40% of the additional vehicle investment costs is covered and the maximum amount a single company can receive is capped at € 500,000.[135] It is welcomed that, pending EU approval, Germany has announced it will cover up to 80% of the additional investment costs with a total funding volume of € 1.16 billion until 2023.[136] It is not yet clear whether the maximum funding cap of € 40,000 would be maintained and whether the subsidy would expire by 2026. Figure 21 shows which impact it would have on the TCO to cover up to 80% of the additional investment and increase the funding cap to € 60,000 until 2026 in combination with the proposed road charging reform (see below).

Road charging

In 2019, the annual federal revenue from petrol and diesel fuel duties amounted to € 37 billion.[137] This tax revenue will gradually diminish and, eventually, disappear altogether and only be partly compensated by the electrification of road transport. To offset this future revenue loss, align the current artificially low cost level with the real externalities caused by road haulage and deliver the necessary steering effect towards zero-emission alternatives, Germany needs to reform its distance-based tolling system for HGVs following the Eurovignette Directive Revision.

Under the revised Eurovignette Directive (currently under negotiation), Germany will have to vary the infrastructure charge from 2023 for those truck categories which are regulated under the CO_2 standards for new HDVs. For this, ICE trucks and ZLEVs will be allocated to five CO_2 emission classes based on their performance against their linear emission reduction trajectory as defined in the CO_2 standards. Member States will also be permitted to keep full infrastructure charge exemptions for ZEVs until the end of 2025, after which the reduction must amount to 50 - 75% compared to the least fuel-efficient ICE trucks in CO_2 emission class 1.

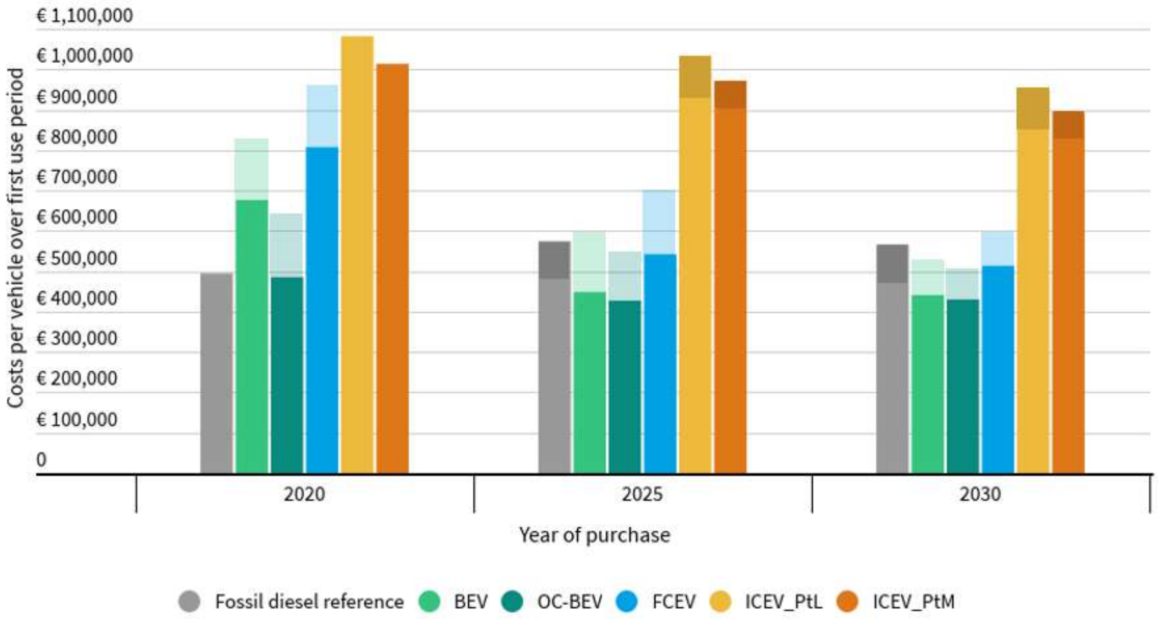
Member States will also have the option to apply a CO_2-based external cost charge as an alternative to varying the infrastructure charge, or to combine both instruments. Member States may also levy an increased external cost charge for CO_2 which may not be higher than twice the reference values set out in the Directive.

Germany has announced to vary the infrastructure charge based on CO_2 in combination with an effective CO_2 external cost charge from 2023.[138] Germany should keep the current ZEV exemption from the infrastructure charge until 2025 and reduce it to 75% compared to CO_2 emission class 1 thereafter.

In addition, Germany should levy a CO_2 external cost charge at twice the reference value which is the equivalent to a CO_2 price of € 200/tCO_2. A reimbursement system will likely be introduced as part of the 'Lkw-Maut' revision. Such a reimbursement should only be applied if CO_2 is levied through an external cost charge at twice the reference value.[139]

Germany must also end the current toll exemption for gas trucks immediately to not further violate EU law. Under the CO_2 variation and only from 2023 onwards, gas trucks will benefit from a toll reduction on the infrastructure charge between 5% and 30% depending on whether they are allocated to CO_2 emission class 2 or 3. Until CO_2 variation enters into force, Euro VI gas trucks must be tolled at the same level as Euro VI diesel trucks to comply with the current and soon-to-be revised Eurovignette Directive.

Figure 21 shows the impact this would have on the TCO in combination with the planned revision of the purchase subsidy. By increasing the purchase subsidy funding rate to 80% of the additional investment costs and revising the road charging scheme as suggested above, long-haul BEVs could possibly reach TCO parity with fossil diesel trucks as early as 2024 and FCEVs soon thereafter.



TCO of long-haul trucks in Germany after purchase subsidy and road charging reform

Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including total vehicle costs (purchase costs and residual value, maintenance & repairs, vehicle taxes, excl. financing costs and VAT), renewable electricity and fuel costs (incl. grid connection fees, transport and distribution costs as well as taxes and levies), infrastructure costs (at high utilisation) and road charges varied based on the Eurovignette Revision. BEV includes opportunity costs due to additional battery weight until 2025.

Figure 21: TCO - after purchase subsidy and road charging reform

7.2. Charging and refuelling infrastructure

Alternative Fuels Infrastructure Directive

Germany should advocate for an ambitious revision of the EU Directive on Alternative Fuels Infrastructure (AFID). The Directive should be changed into a Regulation to ensure swift and harmonised infrastructure deployment. The regulatory scope should be limited to zero-emission technology only. Current infrastructure targets for CNG and LNG vehicles should be phased out by 2025 at the latest.

The AFID should set binding targets for the number of charging points per Member State for 2025 and 2030. Germany will need to deploy around 4,000 (semi)-public and destination chargers by 2025 and at least 14,000 by 2030 (excluding public overnight charging). High-power charging (at least 350 kW) should account for between one third and one half of these charging points. Initial deployment of public high-power charging and destination charging in the first half of the 2020s should focus on the hot spots for road freight activity along the TEN-T network, the so-called 'urban nodes', which should be fully covered by 2025.

Long-haul battery electric trucks will require an initial high-power and megawatt charging (MCS) network along the motorways by 2025, at least one site every 100 km by 2027 and, finally, full MCS coverage every 50 km by 2030. For destination charging, all medium and large logistics hubs should have at least one high-power opportunity charger from 2025. In addition, public overnight chargers (150 kW) will be needed at truck parking areas reaching full coverage by 2030.

Member States should also be required to upgrade the electricity grid infrastructure alongside the TEN-T core network to facilitate MCS charging for battery electric long-haul trucks. ERS should become a recognised technology to allow Member States using it to meet their binding targets for the TEN-T core network. In regards to the deployment of refuelling infrastructure for hydrogen fuel cell trucks, sea ports and their economic hinterland including industrial clusters should be prioritised for initial pilot projects (see below).

Financial support for private and public charging infrastructure

Germany has announced an ambitious funding programme for charging and refuelling infrastructure with a total volume of € 4.1 billion until 2023 for both light- and heavy-duty vehicles.[140] As planned, the Federal Government should introduce a dedicated funding instrument to support transport operators for installing depot and destination charging infrastructure for urban and regional delivery trucks. The programme should also provide explicit funding to upgrade the electricity grid since transport operators are often not able to bear the additional grid-related 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.[141] As a result, utilities offer grid infrastructure upgrades at no additional cost for the vehicle operator.[142]

Megawatt charging infrastructure

Public-private partnerships with truck manufacturers, transport operators, utility companies and grid operators are needed to overcome initial funding restraints, facilitate the knowledge flow between stakeholders and lay the groundwork for the deployment of a country-wide initial megawatt charging (MCS) network from 2025. The recent announcement by a cross-industry consortium to conduct a publicly-funded MCS pilot project by 2023 is an important first step.[143] Germany should consider the funding of similar projects with a specific focus on battery electric long-haul operations along the German trunk motorway network. Such projects should involve utility companies and network operators.

Electric road systems

If electric road systems are to become a reality, they now require concrete political action and closer collaboration between like-minded Member States. Currently, the greatest barrier for ERS deployment is the lack of technological harmonisation and market inertia due to investment uncertainty. It is in the interest of Germany and its European partner countries to develop a mutual understanding on the necessary next steps towards technological harmonisation in order to ensure cross-border interoperability of any potential future infrastructure.

Hydrogen refuelling infrastructure

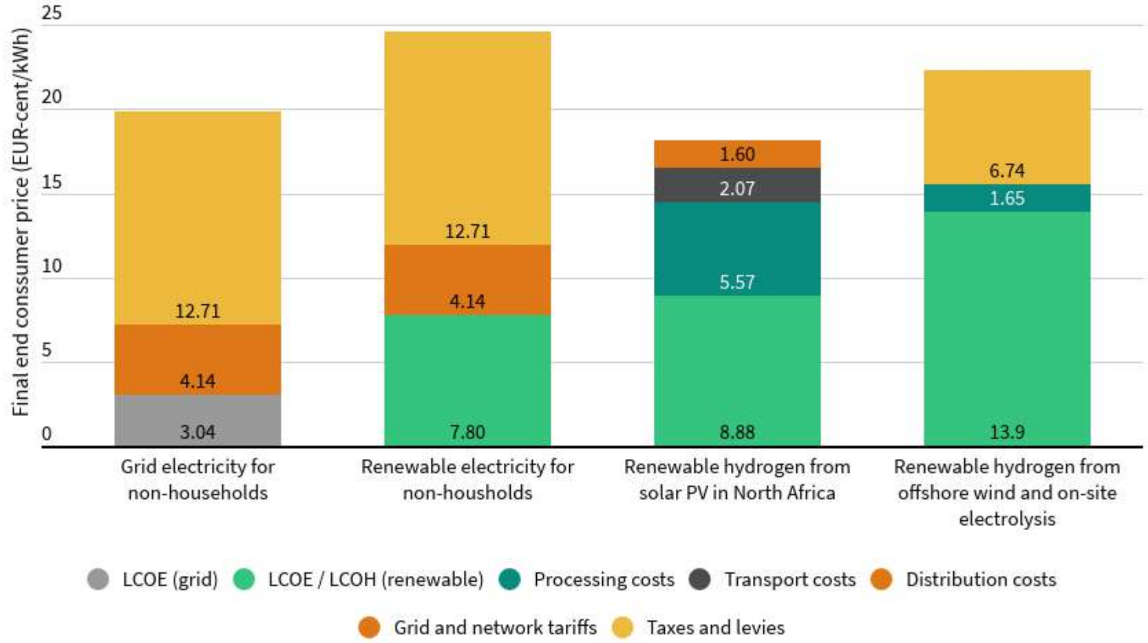
In regards to the deployment of refuelling infrastructure for hydrogen fuel cell trucks, sea ports and their economic hinterland should be prioritised for initial pilot projects. Ports and adjacent industrial clusters represent a no-regret starting point to roll out hydrogen refuelling stations for trucks as this will create synergy effects with hydrogen's future application in the shipping and industry sectors. Sea ports will also serve as major landing terminals for hydrogen imports from offshore or overseas production sites which will improve the initial business case for these hydrogen trucks.

7.3. Energy taxation

Electricity

Figure 22 illustrates how unevenly renewable electricity and hydrogen are currently taxed in Germany. Electricity used by commercial road freight vehicles is currently liable in full to taxes, levies and charges. The renewables surcharge ('EEG-Umlage') is now capped to 20% for transport operators using electric buses for regular services and whose electricity consumption amounts to at least 100 MWh per year.[144] This provision should be extended to the transportation of goods by electric trucks for a limited time period when the German Renewable Energy Sources Act is revised again in 2021. This would help to level the playing field between battery electric and hydrogen trucks as the latter already benefits from a fuel duty exemption and the production of renewable hydrogen is exempt from the renewables levy as well as network tariffs on the electricity input.

Final electricity and hydrogen prices in 2025



Notes: Electricity wholesale prices, network tarrifs, taxes and levies for non-household users with an annual consumption of 500 - 2,000 MWh. Processing costs are due conversion via compression or liquefaction. Transport costs refer to shipping from North Africa to Gerrmany via cryogenic tanker vessel. Distribution costs refer to delivery via cryogenic tanker truck. In Germany, renewable hydrogen production is exempt from the renewables levy ('EEG-Umlage) and network tariffs ('Netzentgelte'); all other taxes and levies on electricity input apply. Hydrogen as a transport fuel is exempt from fuel duty.

Figure 22: Final electricity and hydrogen prices in 2025

Such a reduction would comply with EU law: The Energy Tax Directive explicitly allows Member States to apply a reduced tax rate to electricity supplied to charging stations for electric vehicles after authorisation through a unanimous Council Implementing Decision.[145] The Netherlands is currently applying a reduced tax rate since 2016 and has been authorised by the Council to continue to do so until at least 2025.[146,147] The Federal Government should furthermore advocate for the removal of this unanimity requirement in the upcoming Revision of the EU Energy Taxation Directive (ETD).

Natural gas

Germany is currently applying an extremely low fuel duty rate to natural gas used as a transport fuel (€ 13.90/MWh) regardless whether it is fossil-derived or sustainably-sourced biomethane. The current tax rate will be increased in gradual steps until the original rate of € 31.80/MWh applies from 2027. Germany should adjust the reduced rate so that it only applies to sustainable biomethane which is sourced from advanced waste- and residue-based feedstocks. Fossil-derived natural gas should not benefit from any reduction and be taxed at the normal rate instead. These changes can be introduced through the 2022 Finance Act.

Diesel

Currently low oil prices and growing political willingness to phase out fossil fuel subsidies are a good opportunity to harmonise and simplify fuel and energy tax rates. Despite its higher energy and carbon content, diesel fuel is still being taxed at a lower level than petrol. Diesel and petrol fuel duty rates have furthermore been frozen since 2003. The diesel fuel duty rate should be gradually raised until it reaches the equivalent level of petrol on the basis of their respective energy or carbon content.[148] Such a fuel taxation reform needs to take into account the future regulatory design and CO_2 charge level of both the road charging reform and any exemption scheme from the BEHG (see above).

Alternatively, Germany could also introduce an annual indexation of the fuel duty rates in line with the historical Consumer Prices Index (CPI). The historically observed inflation rate since 1991 has been 1.7% per year on average.[149]

7.4. Supply of zero-emission trucks

There is ample evidence that the demand for zero-emission trucks is growing quickly, but that manufacturers are failing to supply the needed production volume to the market fast enough. The lack of investment certainty for zero-emission trucks is still one of the key barriers holding back production and, consequently, market uptake.

Notwithstanding, the industry is already moving into the right direction: Daimler, the world's biggest truck manufacturer, has 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.[150] Scania has announced that 50% of their truck sales in 2030 will be battery electric.[151] MAN aims for 60% of urban and regional delivery and 40% of long-haul truck sales to be zero-emission by the same date.[152] Renault Trucks targets 35% zero-emission truck sales by 2030.[153]

European CO_2 standards for new HDVs

The EU has adopted its first-ever CO_2 emission performance standards for new HDVs in 2019. To overcome the looming supply gap, Germany should advocate for an ambitious review in 2022 and thereby provide the market signal to truck manufacturers to ramp up the production of zero-emission trucks. The upcoming revision planned for the end of 2022 needs to address a number of shortcomings:

The current average fleet reduction target for 2030 of 30% is wholly insufficient to meet Germany's and the EU's climate targets. A growing part of the 2025 and 2030 targets will be met by accelerating the deployment of ZEVs. The target for 2030 therefore needs to be considerably increased. In addition, the Regulation should set subsequent targets for 2035 and 2040.

With the 2022 review, the European Commission will consider extending the CO_2 standards to the currently unregulated vehicle categories (lighter trucks, trailers, buses and coaches). For this, VECTO certification needs to be extended. The revised CO_2 standards should then also cover the currently unregulated vehicle types (trailers, buses and coaches) and groups (1 - 3, 11, 12 and 16) to the largest extent which is practically implementable.

The ZLEV incentive mechanism should be replaced by a mandatory sales target to oblige manufacturers to sell a certain share of ZEVs out of their total vehicle sales. The share could vary depending on the vehicle category and weight class based on the VECTO categories in order to take due account of specific vehicle characteristics and operational needs. California's Advanced Clean Trucks Regulation sets 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.[154] A 100% ZEV target can provide the legal mechanism to reach a ICE sales phase-out for 2035 below 26 tonnes GVW and for the late 2030s above 26 tonnes GVW (see below).

In line with a ZEV target, the EU should adopt a sales phase-out for new ICE trucks with a GVW below 26 tonnes for 2035 and above 26 tonnes by 2040 at the latest. The EU should make it possible for Member States to set earlier phase-out dates on a voluntary basis. For this, the EU would need to adopt legislative measures allowing those Member States to do so in compliance with EU type-approval and internal market rules.[155] The Federal Government should support the introduction of such a rule at European level which would enable Member States to introduce earlier phase-out dates.

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 German national law as soon as possible.

The same applies to the recent EU Decision setting special rules regarding maximum lengths for cabs delivering improved aerodynamic performance.[156] 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.

Member States were initially legally obliged to transpose this Decision into national law by September 2020 already. The national legislative procedure is already underway and must now be concluded as quickly as possible so that truck manufacturers have certainty for their future vehicle cab development.[157]

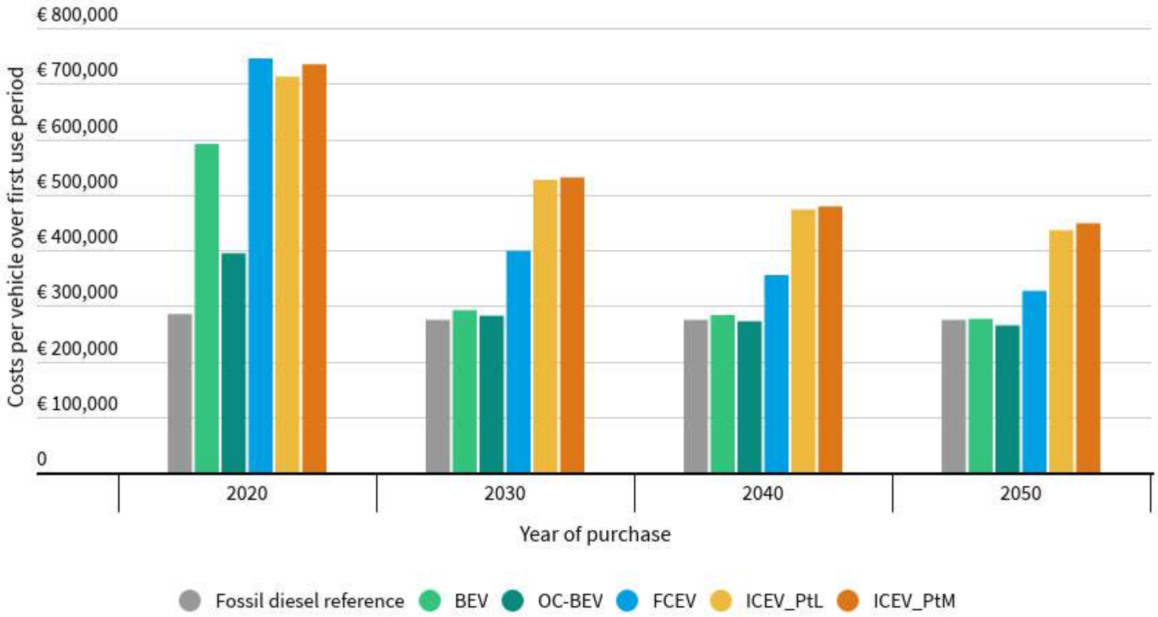
7.5. Zero-emission urban freight

The Federal Government should develop a zero-emission city logistics strategy in close coordination with cities and municipalities. Urban areas should consider introducing zero-emission zones for both light-commercial and heavy-goods vehicles, i.e. vans and trucks, with a view towards the second half of the decade. 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.[158,159] 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.[160]

Annex

Cost sensitivities

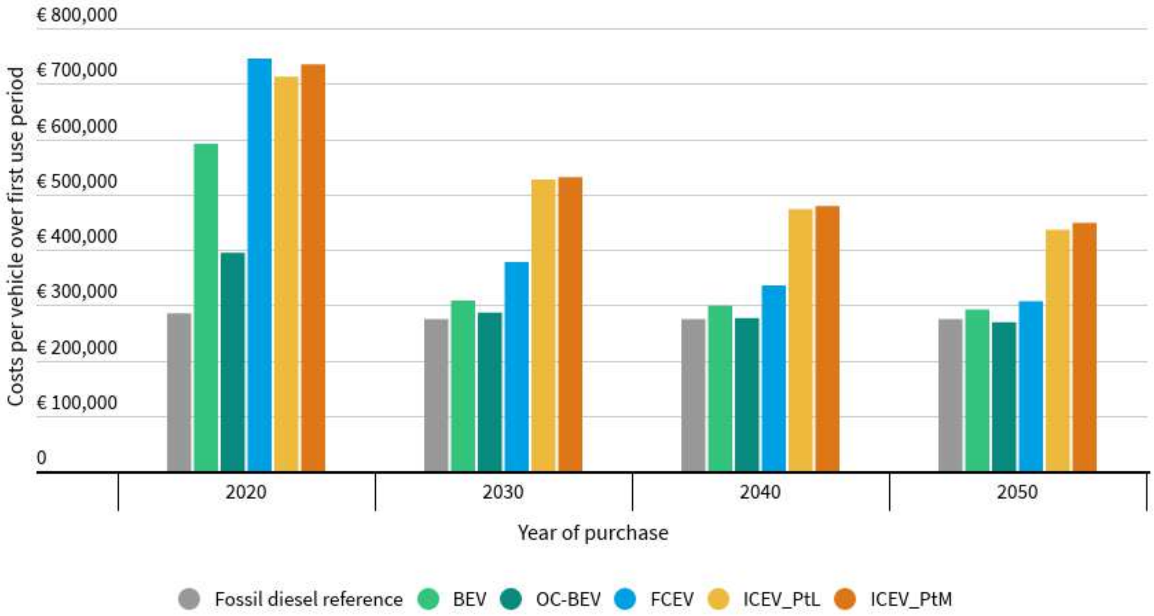
Lifetime system costs of long-haul trucks in Germany
Reduced battery costs



Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including vehicle costs (purchase costs, maintenance & repairs and residual value), renewable electricity and fuel costs and infrastructure costs (at high utilisation). Excluding taxes, levies and road charges except for grid connection fees and electricity transmission and distribution costs. BEV includes opportunity costs due to additional battery weight before 2030.

Lifetime system costs - sensitivity analysis with reduced battery costs

Lifetime system costs of long-haul trucks in Germany
Reduced fuel cell and hydrogen storage tank costs



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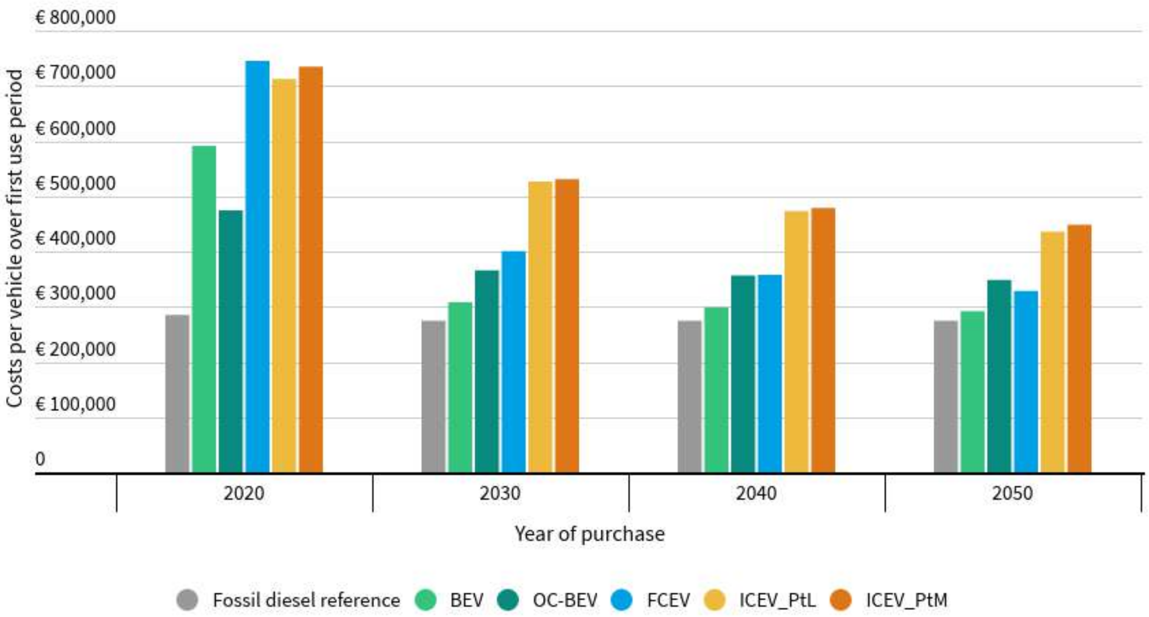
Lifetime system costs - sensitivity analysis with reduced fuel cell and hydrogen storage tank costs

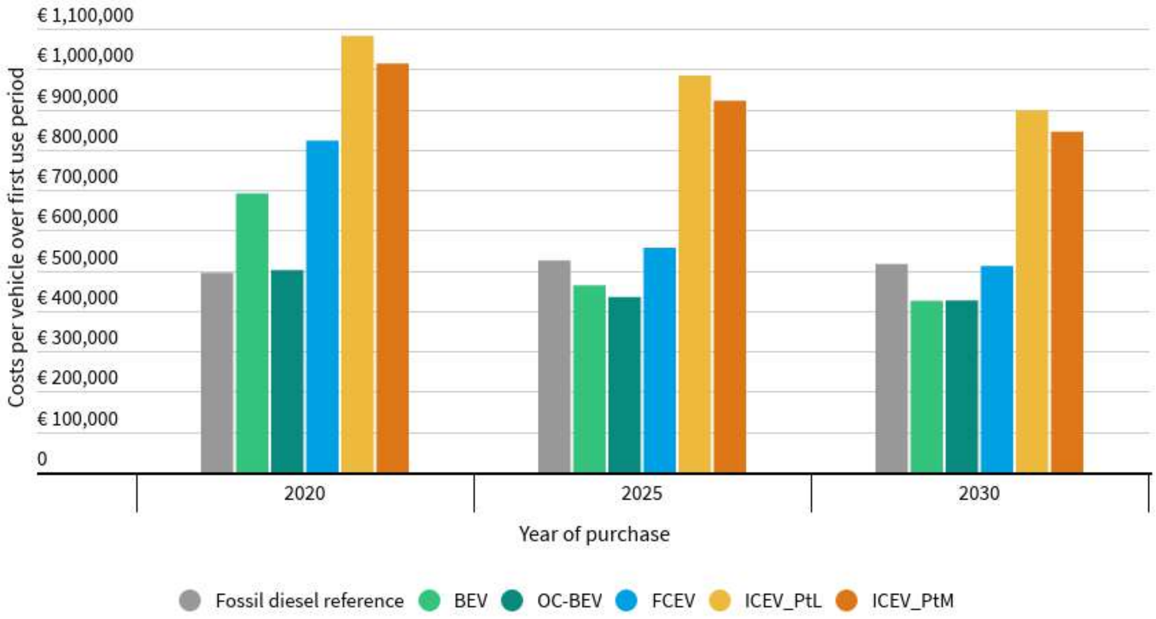
Lifetime system costs of long-haul trucks in Germany
Low utilisation of the overhead catenary infrastructure



Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including vehicle costs (purchase costs, maintenance & repairs and residual value), renewable electricity and fuel costs and infrastructure costs (at high utilisation except for the OC-BEV). Excluding taxes, levies and road charges except for grid connection fees and electricity transmission and distribution costs. BEV includes opportunity costs due to additional battery weight before 2030.

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

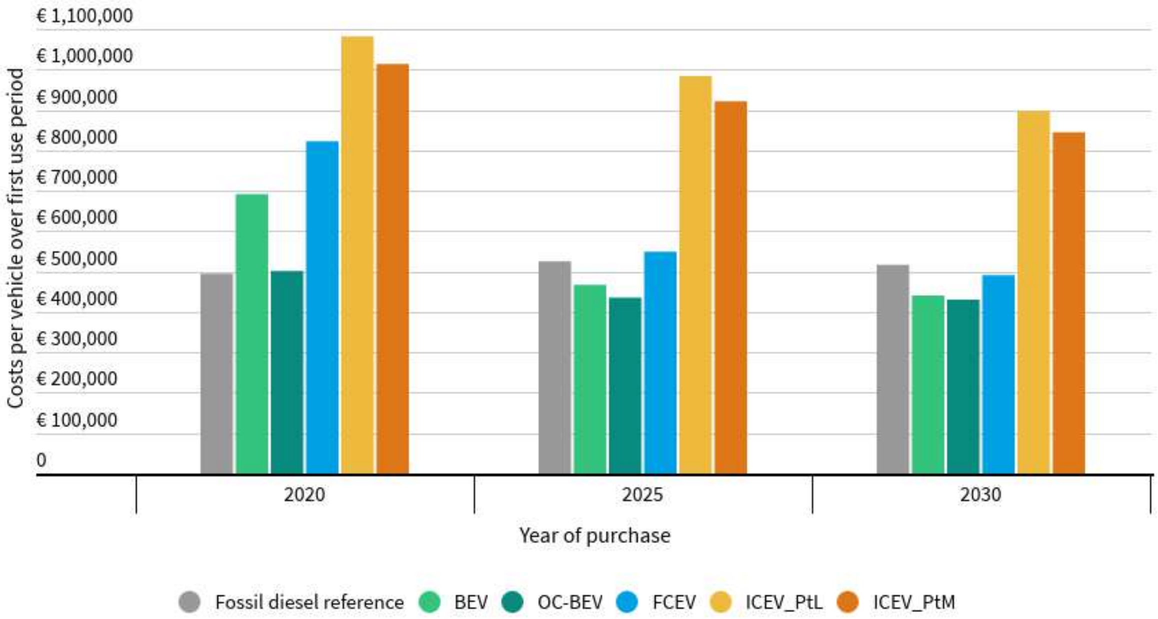
TCO of long-haul trucks in Germany
Reduced battery costs



Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including total vehicle costs (purchase costs and residual value, maintenance & repairs, vehicle taxes, excl. financing costs and VAT), renewable electricity and fuel costs (incl. grid connection fees, transport and distribution costs as well as taxes and levies), infrastructure costs (at high utilisation) and road charges varied based on the Eurovignette Revision. BEV includes opportunity costs due to additional battery weight until 2025.

TCO - sensitivity analysis with reduced battery costs

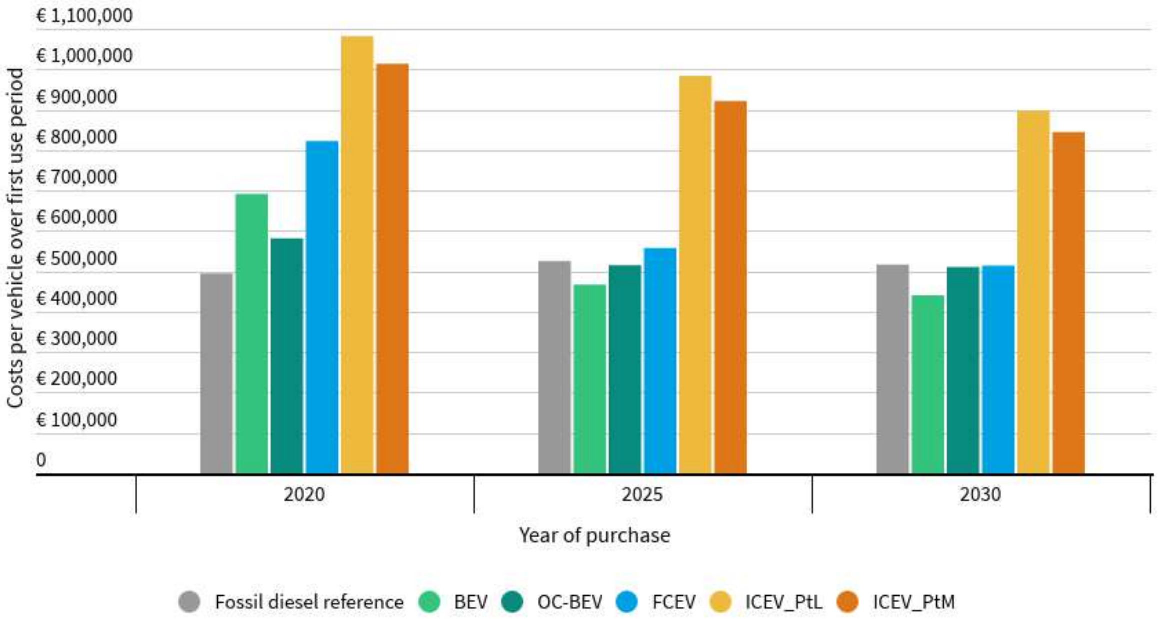
TCO of long-haul trucks in Germany
Reduced fuel cell and hydrogen storage tank costs



Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including total vehicle costs (purchase costs and residual value, maintenance & repairs, vehicle taxes, excl. financing costs and VAT), renewable electricity and fuel costs (incl. grid connection fees, transport and distribution costs as well as taxes and levies), infrastructure costs (at high utilisation) and road charges varied based on the Eurovignette Revision. BEV includes opportunity costs due to additional battery weight until 2025.

TCO - sensitivity analysis with reduced fuel cell and hydrogen storage tank costs

TCO of long-haul trucks in Germany
Low utilisation of the overhead catenary infrastructure



Notes: Costs are for long-haul tractor trailers with 40 tonnes GVW and (at least) 800 km range. Assuming a first use period of 5 years. All vehicles are exlusively powered by renewable energy, including the (OC)-BEV. Including total vehicle costs (purchase costs and residual value, maintenance & repairs, vehicle taxes, excl. financing costs and VAT), renewable electricity and fuel costs (incl. grid connection fees, transport and distribution costs as well as taxes and levies), infrastructure costs (at high utilisation) and road charges varied based on the Eurovignette Revision. BEV includes opportunity costs due to additional battery weight until 2025.

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

Vehicle 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)	1.52	1.34	1.15	1.15	1.15
BEV (plug-to-wheel)	1.60	1.41	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 40 tonnes GVW. Values after 2030 are kept constant except for the FCEV which benefits from an increasing average fuel cell efficiency until 2050. Taking into account fuel efficiency improvements of ICEVs until 2030. For OC-BEVs, above values represent the energy 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 after accounting for battery weight differences.

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).

Vehicle costs

Vehicle		Vehicle costs (excl. financing costs, VAT, purchase subsidy and opportunity costs)				
		2020	2025	2030	2040	2050
ICEV_diesel	Purchase cost	€ 105,484	€ 109,159	€ 115,252	€ 115,252	€ 115,252
	M&R	€ 20,471 p.a.	€ 20,608 p.a.	€ 20,608 p.a.	€ 20,608 p.a.	€ 20,608 p.a.
	Vehicle taxes	€ 561 p.a.	€ 561 p.a.	€ 561 p.a.	€ 561 p.a.	€ 561 p.a.
BEV	Purchase cost	€ 417,255	€ 200,006	€ 145,346	€ 145,346	€ 145,346
	M&R	€ 14,359 p.a.	€ 14,359 p.a.	€ 14,359 p.a.	€ 14,359 p.a.	€ 14,359 p.a.
	Vehicle taxes	€ 5 p.a.	€ 5 p.a.	€ 5 p.a.	€ 5 p.a.	€ 5 p.a.
OC-BEV	Purchase cost	€ 203,547	€ 136,872	€ 112,028	€ 112,028	€ 112,028
	M&R	€ 14,632 p.a.	€ 14,632 p.a.	€ 14,632 p.a.	€ 14,632 p.a.	€ 14,632 p.a.
	Vehicle taxes	€ 5 p.a.	€ 5 p.a.	€ 5 p.a.	€ 5 p.a.	€ 5 p.a.
FCEV	Purchase cost	€ 391,802	€ 209,572	€ 157,096	€ 155,647	€ 154,318
	M&R	€ 26,324 p.a.	€ 18,735 p.a.	€ 18,735 p.a.	€ 18,735 p.a.	€ 18,735 p.a.

	Vehicle taxes	€ 5 p.a.	€ 5 p.a.	€ 5 p.a.	€ 5 p.a.	€ 5 p.a.
ICEV_PtL	Purchase cost	€ 105,484	€ 109,159	€ 115,252	€ 115,252	€ 115,252
	M&R	€ 20,471 p.a.	€ 20,608 p.a.	€ 20,608 p.a.	€ 20,608 p.a.	€ 20,608 p.a.
	Vehicle taxes	€ 561 p.a.	€ 561 p.a.	€ 561 p.a.	€ 561 p.a.	€ 561 p.a.
ICEV_PtM	Purchase cost	€ 128,339	€ 120,075	€ 126,777	€ 126,777	€ 126,777
	M&R	€ 21,894 p.a.	€ 20,389 p.a.	€ 20,389 p.a.	€ 20,389 p.a.	€ 20,389 p.a.
	Vehicle taxes	€ 561 p.a.	€ 561 p.a.	€ 561 p.a.	€ 561 p.a.	€ 561 p.a.

Sources: T&E calculations based on Kühnel et al. (2018), Meszler et al. (2018), ACEA (2020), Zoll (2020) BloombergNEF (2020), Moultak et al. (2017), Ricardo Energy & Environment (2019), Hall et al. (2019), U.S. Department of Energy (2019) and Roland Berger (2020).

Energy costs

Electricity and electricity-based fuel production in Europe		**€-cent/kWh**				
		2020	**2025**	**2030**	**2040**	**2050**
Fossil diesel	Total	5.34	5.34	5.34	5.34	5.34
	Total incl. taxes and levies	10.07	10.07	10.07	10.07	10.07
Renewable electricity (commercial	Levelised cost of electricity	9.22	7.80	7.23	6.14	5.11
	Transport to Germany	*Grid connection fees included in LCOE*				

use)	Distribution in Germany	4.14	4.14	4.14	4.14	4.14
	Total	13.36	11.94	11.37	10.28	9.25
	Total incl. taxes and levies	26.07	24.65	24.08	22.99	21.96
Renewable hydrogen from offshore wind on-site production (PPA)	Levelised cost of hydrogen	16.70	13.90	12.49	10.00	7.91
	Compression	1.96	1.65	1.35	1.04	0.73
	Transport to Germany	*not applicable*				
	Distribution in Germany	*not applicable*				
	Total	18.65	15.56	13.83	11.04	8.64
	Total incl. taxes and levies	25.60	22.29	20.37	17.21	14.48
Power-to-liquid from offshore wind in the North Sea	Levelised cost of fuel production	27.48	23.71	20.86	17.42	14.49
	Transport to Germany	*not applicable*				
	Distribution in Germany	1.00	1.00	1.00	1.00	1.00
	Total	28.48	24.71	21.87	18.42	15.49
	Total incl. taxes and levies	41.90	37.86	34.77	30.85	27.52
Power-to-methane from	Levelised cost of fuel production	26.16	22.34	19.56	16.08	13.74

offshore wind in the North Sea	Liquefaction	0.69	0.68	0.67	0.64	0.61
	Transport to Germany	*not applicable*				
	Distribution in Germany	1.10	1.10	1.10	1.10	1.10
	Total	27.95	24.12	21.33	17.82	15.45
	Total incl. taxes and levies	38.03	34.83	32.67	28.70	25.92

Electricity-based fuel production in North Africa		**€-cent/kWh**				
		2020	**2025**	**2030**	**2040**	**2050**
Renewable hydrogen from solar PV in North Africa	Levelised cost of hydrogen	10.18	8.88	7.83	6.10	4.86
	Liquefaction	6.73	5.57	4.41	3.55	2.69
	Transport to Germany	2.07	2.07	2.07	2.07	2.07
	Distribution in Germany	1.60	1.60	1.60	1.60	1.60
	Total	20.58	18.13	15.91	13.33	11.23
	Total incl. taxes and levies	20.58	18.13	15.91	13.33	11.23
Power-to-liquid from solar PV in	Levelised cost of fuel production	18.90	17.10	14.74	12.29	10.49

North Africa	Transport to Germany	0.04	0.04	0.04	0.04	0.04
	Distribution in Germany	1.00	1.00	1.00	1.00	1.00
	Total	19.95	18.15	15.78	13.33	11.53
	Total incl. taxes and levies	24.67	22.86	20.50	18.05	16.25
Power-to-methane from solar PV in North Africa	Levelised cost of fuel production	17.83	15.94	13.62	11.11	9.88
	Liquefaction	0.69	0.68	0.67	0.64	0.61
	Transport to Germany	0.21	0.21	0.21	0.21	0.21
	Distribution in Germany	1.10	1.10	1.10	1.10	1.10
	Total	19.83	17.93	15.61	13.07	11.80
	Total incl. taxes and levies	21.22	20.22	18.79	16.25	14.98

Sources: T&E calculations based on Destatis (2020), Zoll (2020), Agora Verkehrswende et al. (2018), Destatis (2021), U.S. Department of Energy (2019), Pfennig et al. (2017), Runge et al. (2020), Hydrogen Council (2020), EnWG (2020), Mottschall et al. (2019), Bundesnetzagentur (2020), Fasihi et al. (2016) and and Bünger et al. (2016).

Infrastructure costs

Electric charging station			
Parameters	**2020**	**2025**	**2030**

High-power charger (1.2 MW)	Charging time	45 minutes for 400 km range		
	Supplied vehicles per day	10		20
	Service life	15 years		
	Capital expenditure	€ 464,344	€ 420,000	€ 374,186
	Operational expenses	€ 4,643 p.a.	€ 4,200 p.a.	€ 3,742 p.a.
Overnight charger (150 kW)	Charging time	8 hours for 800 km range		
	Supplied vehicles per day	0.83		0.91
	Service life	15 years		
	Capital expenditure	€ 75,000	€ 69,545	€ 65,000
	Operational expenses	€ 750 p.a.	€ 696 p.a.	€ 650 p.a.
Total infrastructure costs per vehicle per year (high utilisation)		€ 10,463 p.a.	€ 9,621 p.a.	€ 6,917 p.a.

Electric road system				
Parameters		**2020**	**2025**	**2030**
Overhead	System voltage	1,500 V_{DC}		

catenary system	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)	€ 3.05 million
	Capital expenditure per MW (both directions)	€ 762,500
	Operational expenses per km (both directions)	€ 61,000 p.a.
Total infrastructure costs per vehicle per year (high utilisation)		€ 5,338 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	42 kg$_{H2}$	37 kg$_{H2}$	32 kg$_{H2}$
	Dispenser flow rate	3.6 - 7.2 kg$_{H2}$/min		
	Supplied vehicles per day	110		166
	Service life	15 years		
	Capital expenditure	€ 6.97 million	€ 6.30 million	€ 5.61 million
	Operational expenses	€ 69,652 p.a.	€ 63,000 p.a.	€ 56,128 p.a.
Total infrastructure costs per vehicle per year (high utilisation)		€ 4,855 p.a.	€ 4,391 p.a.	€ 2,592 p.a.

LNG refuelling station				
Parameters		**2020**	**2025**	**2030**
Mid-sized LNG refuelling station	Total refuelling capacity	17,000 kg$_{LNG}$		
	Mean refuelling quantity per vehicle	119 kg$_{LNG}$	106 kg$_{LNG}$	93 kg$_{LNG}$
	Supplied vehicles per day	55		83

	Service life	15 years		
	Capital expenditure	€ 1.03 million	€ 1.03 million	€ 1.03 million
	Operational expenses per year	€ 27,080 p.a.	€ 27,080 p.a.	€ 27,080 p.a.
Total infrastructure costs per vehicle per year (high utilisation)		€ 1,746 p.a.	€ 1,746 p.a.	€ 1,157 p.a.

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

Road charges

Vehicle	Charge	2020	2025	2030
ICEV_diesel	Infrastructure charge	€-cent 17.40/km	€-cent 17.40/km	€-cent 17.40/km
	External cost charge for noise and air pollution	€-cent 1.30/km	€-cent 1.30/km	€-cent 1.30/km
	External cost charge for CO_2	-	€-cent 8.00/km	€-cent 8.00/km
	Total	€-cent 18.70/km	€-cent 26.70/km	€-cent 26.70/km
BEV	Infrastructure charge	-	-	€-cent 4.35/km
	External cost charge for air and noise pollution	-	€-cent 0.20/km	€-cent 0.20/km
	External cost charge for CO_2	-	-	-
	Total	-	€-cent 0.20/km	€-cent 4.55/km

OC-BEV	Infrastructure charge	-	-	€-cent 4.35/km
	External cost charge for air and noise pollution	-	€-cent 0.20/km	€-cent 0.20/km
	External cost charge for CO_2	-	-	-
	Total	-	€-cent 0.20/km	€-cent 4.55/km
FCEV	Infrastructure charge	-	-	€-cent 4.35/km
	External cost charge for air and noise pollution	-	€-cent 0.20/km	€-cent 0.20/km
	External cost charge for CO_2	-	-	-
	Total	-	€-cent 0.20/km	€-cent 4.55/km
ICEV_PtL	Infrastructure charge	€-cent 17.40/km	€-cent 17.40/km	€-cent 17.40/km
	External cost charge for air and noise pollution	€-cent 1.30/km	€-cent 1.30/km	€-cent 1.30/km
	External cost charge for CO_2	-	€-cent 8.00/km	€-cent 8.00/km
	Total	€-cent 18.70/km	€-cent 26.70/km	€-cent 26.70/km
ICEV_PtM	Infrastructure charge	€-cent 17.40/km	€-cent 12.18/km	€-cent 12.18/km
	External cost charge for air and noise pollution	€-cent 1.30/km	€-cent 1.30/km	€-cent 1.30/km

	External cost charge for CO_2	-	€-cent 8.00/km	€-cent 8.00/km
	Total	€-cent 18.70/km	€-cent 21.48/km	€-cent 21.48/km

Sources: T&E calculations based on European Commission (2013), Kühnel et al. (2018), BFStrMG (2020) and Council of the European Union (2020).

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