International Transport Forum

Decarbonising Europe's Trucks
How to Minimise Cost Uncertainty

Case-Specific Policy Analysis

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The International Transport Forum

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Abbreviations and acronyms

BEV	Battery electric vehicle
ERS	Electric road system
ERSV	Electric road system vehicle
FCEV	Fuel cell electric vehicle
GHG	Greenhouse Gas
HDV	Heavy-duty vehicle
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
kg	Kilogram
kW	Kilowatt
kWe	Kilowatt-electric
kWh	Kilowatt hour
MW	Megawatt
MWh	Megawatt hour
TCO	Total cost of ownership
ZEV	Zero-emission vehicle

Glossary

Overhead catenary electric road system	Infrastructure enabling vehicles to draw electricity from cables installed over a road. A pantograph is used to connect the vehicle to the cables (in a similar fashion to electric trains).
Pantograph	A mechanical linkage used to connect a vehicle to overhead catenary cables. Electrical contact between the pantograph and the wires allows the vehicle to draw electricity from the cables whilst driving.
Powertrain	The source of power used to provide motion to a vehicle. This includes the motor, transmission and fuel/energy storage system.
Total cost of ownership (TCO)	The sum of all expenditure over the ownership period of a vehicle including: purchase costs, residual value at end of life, fuel/energy costs and operation and maintenance
Zero-emission vehicle (ZEV)	A vehicle producing no tailpipe emissions at the point of use. Examples include battery electric vehicles and fuel cell electric vehicles.

Executive summary

What we did

This report investigates the feasibility of decarbonising heavy-duty trucks in Europe with zero-emission powertrain technologies. It compares three technological approaches: battery electric vehicles, electric road systems and hydrogen fuel cell vehicles. Currently, uncertainty regarding their relative merits hampers decision-making about which technologies to pursue and postpones decarbonisation.

This report investigates the financial viability of the three different technologies and compares it to that of conventional diesel vehicles by examining their total cost of ownership. The analysis accounts for the significant uncertainty associated with each technology for the first time by exploring 1 000 unique scenarios for each powertrain technology and across nine different vehicle size segments in Europe. The scenarios range from conservative to ambitious in their assumptions about the future of each powertrain technology to explore a broad spectrum of possible solutions. By explicitly quantifying the uncertainty associated with each technology and exploring a range of vehicle size segments, the analysis offers a greater understanding of the potential of zero-emission powertrain technologies.

What we found

This analysis finds that zero-emission vehicles should generally become cost-competitive with diesel-propelled trucks between 2030 and 2040 across all vehicle sizes. When exactly zero-emission vehicles will become cost-competitive with traditional trucks varies with vehicle size: the smallest vehicle categories could reach parity on total cost of ownership with diesel vehicles in 2022. Larger road freight vehicles are more likely to be cost-competitive around 2035.

The total cost of ownership of trucks varies significantly between the three powertrain technologies examined. Battery electric vehicles (BEVs) and electric road system vehicles (ERSVs) – which use catenaries installed above roads to supply vehicles with electricity – have the potential to be the most cost-competitive technologies in Europe due to their energy efficiency and low operational costs, which offset upfront purchase costs.

How battery electric trucks and ERSVs will compare in terms of cost is not yet clear, as their total cost of ownership is comparable in most scenarios. BEVs will likely cost more to purchase and face greater operational constraints than vehicles using an electric road system, which could impede their rapid adoption. Conversely, it is unclear how quickly electric road systems might be deployed, and they would face significant upfront construction costs, which would need government support.

A clearer understanding of the deployment timelines for the required infrastructure – charging stations for battery electric vehicles, overhead contact lines for electric road systems – is needed to allow industry and policy makers to prioritise and understand how these technologies may complement each other.

Based on the scenarios explored, hydrogen fuel cell electric vehicles (FCEVs) are less competitive than the other two zero-emission technologies. FCEVs are cost competitive in only a small number of marginal cases that assume ambitiously low hydrogen fuel costs and very conservative assumptions for BEVs. This suggests that FCEVs might play a niche role in the future fleet of heavy-duty road vehicles, which in turn raises doubts about whether large-scale hydrogen refuelling infrastructure would be sufficiently utilised. At least for Europe, the results of the analysis thus call into question whether policies should necessarily remain technology-neutral regarding the mass-market adoption of hydrogen as a fuel for trucks. That said, it is possible that these findings apply to the European truck market only. FCEVs might offer a decarbonisation solution in other regions where road freight covers longer distances.

Progress in improving energy efficiency reduces future uncertainty about vehicles' total cost of ownership, as low energy efficiency increases owners' exposure to fluctuating energy costs. Promoting energy-efficient powertrain options and other efficiency-enhancing solutions for vehicles, such as improved aerodynamics, will reduce the effect of rising energy prices and increase the probability of lowering emissions.

A number of barriers could delay the adoption of zero-emission vehicles. Truck operators may have insufficient capital for the required investments. The supporting infrastructure required may not (yet) be deployed. Behavioural factors such as a hesitancy to switch to new technologies requiring changes in operations as well as imperfect knowledge and foresight may also hamper adoption. Policies targeting such barriers are essential to strengthen the market's confidence in the most promising vehicle technologies.

What we recommend

Ensure that policies to promote direct electrification of trucks remain technology-neutral

Both battery-electric vehicles and electric road system vehicles can be cost-effective replacements for diesel trucks. Battery electric trucks are well placed to be adopted in the short term in certain market segments. However, it is unclear whether electric road systems could play a complementary role helping to decarbonise the most challenging road freight applications. Policy towards the electrification of trucks should therefore avoid closing the door to either and both technologies should be actively considered in policy discussions about future infrastructure deployment. Short-term technology-neutral policies include strengthening the capacity of the electricity grid along main roads so it can feed charging stations for battery-electric vehicles as well as electric road systems along those routes with potentially sufficient demand.

Launch targeted studies and pilot projects to assess the merits of electric road systems for road freight decarbonisation

Given the uncertainties about the relative merits of battery electric trucks and electric road systems, only further detailed assessments will clarify which technology is financially more viable and how they might complement each other to deliver the largest reductions in carbon dioxide (CO_2) emissions. Pilot projects to test overhead catenary electric road systems and high-power charging systems for battery electric vehicles will be invaluable to better understand the real-world infrastructure needs, operational costs and realistic timelines for rolling out such infrastructure.

Further investigate decarbonisation technologies for particularly challenging road freight applications

Electrifying heavy-duty road freight with battery electric trucks or electric road systems may be challenging for certain niche use cases. Further investigations are needed to better understand how other technologies could provide a complementary role to electrification in decarbonising such road freight applications. It is possible that hydrogen and other propulsion technologies not included in this analysis may be necessary to reduce the carbon intensity of trucks in a limited number of road freight sectors, even if they are unlikely to be cost-competitive for mass-market applications.

Introduce policies that help zero-emission vehicles become cost-competitive sooner

Accelerating the adoption of zero-emission vehicles requires targeted policy support. The high upfront purchase costs of zero-emissions vehicles present a barrier to large-scale adoption, particularly for small trucking companies. Differentiated purchase subsidies and low-interest loans for the purchase of zero-emission vehicles, together with road pricing and carbon taxation, would make them cost competitive with diesel trucks before 2030 and help accelerate the decarbonisation of the road freight sector. Such policies can be designed to be time-limited, revenue-neutral and would reduce the range of uncertainty on the adoption of zero-emission vehicles.

Accelerate the deployment of zero-emission vehicle infrastructure

The adoption of zero-emission vehicles will not be possible without enabling infrastructure. Policy makers should set clear and ambitious targets for its deployment. They should provide targeted financial support and accelerate procedures for planning permission where possible. In doing so, they can create market confidence and help reduce uncertainty. Any policy actions should prioritise those infrastructure solutions most likely to be highly utilised and cost competitive in the long term. Low-risk opportunities include speeding up the construction of depot charging infrastructure and reinforcing electricity grids along main roads and in areas of high future demand.

Strengthen regulations that make trucks more energy-efficient

Many ways exist to improve the energy efficiency of trucks, including aerodynamic improvements and vehicle weight reduction. Promoting energy-efficiency improvements (e.g. by strengthening CO_2 emissions standards) protects against rising energy costs and reduces uncertainty regarding the total cost of ownership of vehicles. Efficiency improvements can also help to accelerate the viability of zero-emission vehicles by increasing the vehicle range.

In brief: Six recommendations for adopting zero-emission vehicles

This analysis of zero-emission heavy-duty road freight vehicles shows that battery electric vehicles and electric road system vehicles are the most cost-efficient and effective technologies for reducing carbon dioxide (CO_2) emissions in the European heavy-duty road freight sector. Policy efforts should focus on enabling their implementation and success.

The rapid decarbonisation of the heavy-duty road freight sector is essential to meeting the goals of the Glasgow Climate Pact adopted at the 2021 UN Climate Change Conference (COP26). Active policy interventions by governments to help promote zero-emission road freight are essential in light of the speed of the required CO_2 emissions reductions. Given this urgency, policy makers do not have the luxury of pursuing all technological avenues equally. They must lay the regulatory foundation to support the technologies with the most promise.

A common principle in technology policy is that of "technology neutrality" – that is, setting a policy goal, such as emissions reduction, without being prescriptive about the technology used to attain the goal. The advantage of technology neutrality is that it allows market forces to meet policy goals in a cost-effective way and avoids closing the door to future technologies. Successful examples enacted in a number of countries include CO_2 emissions standards for new vehicles, which set a target emissions intensity that manufacturers need to meet regardless of the technology used.

The challenge to technology neutrality comes with infrastructure policies. Adopting new powertrain technologies in heavy-duty road freight requires the construction of supporting infrastructure and will need government financial support to overcome market risk. Since governments cannot fund infrastructure for all technologies equally, there inevitably has to be a prioritisation, in which strict technology neutrality is no longer maintained. This prioritisation must focus on the technologies with the greatest potential for rapid emissions reductions and cost-competitiveness.

1. Ensure that policies to promote direct electrification of trucks remain technology-neutral

The cost-competitiveness of new technologies is impacted by economies of scale and the level of utilisation of recharging and refuelling infrastructure. Technologies must be able to gain a sufficient share of the market to lower vehicle production costs and intensively use an infrastructure network. This analysis finds that both BEVs and ERSVs could be cost-competitive with conventional internal combustion engine vehicles (ICEVs) in Europe, suggesting their potential to gain a large market share with the appropriate policy support.

BEVs, in particular, seem well-placed to enter the heavy-duty vehicle (HDV) market in the short term. However, there remains uncertainty about a complementary need for electric road systems (ERS) in the longer term. Until there is greater clarity on the relative roles of BEVs and ERSVs, policies should remain technology neutral, promoting both where possible, and avoid closing the door on either. Policies may achieve that end by, for example, strengthening the electricity grid's capacity along main roads with potentially high electricity demand since this can benefit all zero-emission vehicle (ZEV) technologies. Both

technologies should be actively considered in policy discussions about future infrastructure deployment for zero-emission vehicles.

2. Launch targeted studies and pilot projects to assess the merits of electric road systems for road freight decarbonisation

The total cost of ownership of BEV and ERSV technologies remain similar in most scenarios. However, there remains uncertainty about ERS design and business models, which could alter their financial feasibility. Additionally, the primary actors differ between the two technologies. Governments will need to be primarily responsible for the construction of ERS and provide financial support for the high upfront infrastructure costs and long payback periods needed for ERSVs to be competitive. Conversely, the adoption of BEVs can be more incremental and shouldered by the private sector to a greater extent, with complementary support from governments to accelerate the transition.

Further detailed assessments are needed to understand which technology can offer the most significant financial and CO_2 emissions savings, in addition to energy and resource efficiency benefits. It is possible that BEVs may impose greater technical or operational constraints on truck operators that could limit their adoption under real-world operations. Conversely, ERS would likely take significant time to build and would have to be highly utilised upon completion. Pilot tests of overhead catenary electric road systems and high-power BEV chargers are needed, to better understand the real-world infrastructure costs, operational characteristics and time scales involved in their adoption. Both Germany and the United Kingdom have recently announced plans to construct sections of ERS above motorways for trials and comparisons with other heavy-duty road freight technologies (BMVI, 2021; UK DfT, 2021).

3. Further investigate decarbonisation technologies for particularly challenging road freight applications

This analysis finds that hydrogen fuel cell electric vehicles (FCEVs) are unable to compete with other vehicle technologies extensively. It is possible that FCEVs may be used in niche applications; however, the small scale of the potential market means that achieving significant economies of scale in production volumes will be a challenge. Furthermore, the required network of hydrogen refuelling infrastructure would have to be government-financed at significant costs. If the infrastructure network is not sufficiently utilised due to a small share of FCEVs in circulation, governments risk creating stranded assets or locking in requirements for long-term public subsidies. Similar findings pointing to the marginal role of FCEVs have been highlighted by the Traton group of European truck manufacturers (Gründler and Kammel, 2021), among others (Plötz, 2022).

It is possible that these findings are specific to the European truck market and that FCEVs could offer a solution in other regions with longer distance range requirements. However, for Europe, the analysis calls into question whether hydrogen refuelling infrastructure should benefit from a similar level of government support as direct electrification technologies, which are better-placed to enter the mass market.

This does not mean there are not useful applications for FCEVs. A greater understanding of particularly challenging road freight applications would be beneficial to contextualise the role of alternative low-emission road freight technologies. Assessments need to consider the infrastructure requirements in such niche use-cases and its potential utilisation.

4. Introduce policies that help zero-emission trucks become cost-competitive sooner

The analysis in this report finds that the total cost of ownership of zero-emission vehicles could be competitive with conventional diesel vehicles. The smallest vehicle segments can reach parity in ownership costs before 2030 and larger vehicle segments will follow shortly thereafter. However, every conventional diesel vehicle sold in the meantime will lock in additional emissions. Governments can help to accelerate their replacement with ZEVs by introducing dedicated policy support that kick-starts the economies of scale that will lower ZEV purchase costs.

Electric vehicles' future cost-competitiveness with diesel remains uncertain. This is due to a range of factors, including the costs of diesel, electricity and batteries. The high upfront purchase costs of many ZEV solutions can present particular barriers to adoption. Possible measures to overcome these challenges include differentiated purchase incentives and low-interest-rate loans to reduce vehicle financing costs. Additional policy measures that could significantly improve the total cost of ownership of ZEVs compared with conventional vehicles include differentiated road pricing and carbon and fuel taxation. For example, this report finds that applying a carbon price of EUR 100 per tonne of CO_2 to the trucking sector would allow electric vehicles to be cost-competitive before 2030.

5. Accelerate the deployment of zero-emission vehicle infrastructure

Some of the most important measures for the successful adoption of ZEVs involve stimulating the construction of charging and refuelling infrastructure, including necessary electricity grid upgrades. There are important differences between the three ZEV technologies explored in this report in terms of the barriers to infrastructure roll-out.

For BEVs, there is already a substantial roll-out of charging infrastructure for passenger cars that truck operators and manufacturers may be able to leverage. Recent announcements by truck manufacturers highlight that the private sector is already willing to act. An example is the 2021 joint venture between European manufacturers Daimler Trucks, Volvo Group and the Traton Group. It aims to deploy at least 1 700 high-power charging points by 2026 with a total investment of EUR 500 million (Daimler Trucks, 2021). However, more action will be necessary. The deployment of ZEV infrastructure will take time, requiring energy production, transmission and distribution infrastructure. It is therefore imperative to begin as soon as possible.

This report finds that the majority of energy needs for BEV trucks could be supplied with depot charging, where truck operators may have greater agency to install their own charging infrastructure and ensure high utilisation. However, small operators may not have the financial means to install chargers, particularly if grid infrastructure needs to be strengthened and costs are passed on to truck operators. Governments can provide support through targeted loans for ZEV infrastructure, potentially differentiated by the size of the trucking company, to help smaller, more capital-constrained companies.

Governments can also help to accelerate the roll-out of grid infrastructure by helping to reduce permitting timescales and potentially offering support to reduce market risk, given the uncertain speed of adoption of ZEVs, which has an important impact on the utilisation of infrastructure and its financial viability. Policies improving grid infrastructure along roads can also be considered to be technology neutral since they can help facilitate BEVs, ERSVs and, potentially, hydrogen refuelling infrastructure involving electrolysis near roads. Depot charging can also be useful for all three ZEV technologies making them low-regret avenues to pursue.

6. Strengthen regulations that make trucks more energy-efficient

Energy price shocks in 2022 significantly increased the cost of road freight, with diesel prices rising by 40% in July compared with the previous year (UK BEIS, 2022). The worse the energy efficiency of a vehicle, the more energy costs raise vehicle ownership costs. Energy-efficiency improvements can therefore help protect the sector from future high energy prices and give truck operators greater confidence in the cost of their operations.

Strengthening CO_2 emissions standards of new vehicles can help to promote the adoption of more energy-efficient vehicles. Aerodynamic improvements and light-weighting can already help to reduce the operating costs of existing vehicles; strengthening emissions standards will accelerate their adoption. Stringent regulations can also help promote new energy-efficient powertrains such as battery electric vehicles, which can further improve fleet energy efficiency and ensure the sector's resilience.

A call out to stakeholders

The findings of this report, particularly regarding the role of FCEVs, may run counter to current consensus. The European Commission's Alternative Fuels Infrastructure Regulation (European Commission, 2021a), for example, sets infrastructure provisions for both BEV and FCEV trucks (with little consideration of ERS). The analysis in this report aims to be transparent and examine a broad range of possible futures. The ITF invites an open dialogue building on additional evidence to further refine assessments of different technology pathways in order to minimise uncertainty in the decarbonisation of the heavy-duty road freight sector.

Zero-emission trucks: The road to carbon dioxide reduction

Globally, 68% of surface freight (road, rail and inland waterways) is carried by road vehicles. These vehicles account for 73% of freight transport greenhouse gas (GHG) emissions. Demand for road freight is expected to more than double by 2050. Without further policy action, this will lead to higher levels of GHG emissions (ITF, 2021b).

Several actions can reduce emissions from the road freight sector. Aerodynamic design, eco-driving and increasing average vehicle loads through improved logistics can improve vehicle energy efficiency and achieve short-term gains (ITF, 2018). Longer-term solutions to reduce truck emissions include reducing demand, removing the most polluting vehicles from roads and improving diesel engine efficiencies. However, these actions alone will not suffice to effectively tackle the dangers of climate change and meet government aspirations to keep global temperature rises in line with the Paris Agreement (IEA, 2021b).

The advantages of zero-emission vehicles

One of the decarbonisation solutions with the most significant potential to reduce road freight emissions is to adopt zero-emission vehicle (ZEV) powertrains. The most prominent ZEV powertrains considered today include battery electric vehicles (BEV), electric road system vehicles (ERSV) with overhead catenary pantograph and hydrogen fuel cell electric vehicles (FCEV).

Table 1. Definitions of different powertrains

Powertrain type	Description
Internal combustion engine vehicle (ICEV)	A conventional diesel engine vehicle which currently dominates the heavy-duty vehicle market globally.
Battery electric vehicle (BEV)	A vehicle using a fully electrified powertrain and a large battery.
Electric road system vehicle (ERSV)	A battery electric vehicle using an overhead catenary electric road system with a pantograph. ERSVs have smaller battery requirements than BEVs.
Fuel cell electric vehicle (FCEV)	A vehicle using hydrogen in a fuel cell to power an electrified powertrain.

Zero-emission vehicles produce no GHG emissions during vehicle use and can significantly reduce air-pollutant emissions. There are emissions produced during the manufacture of zero-emission vehicles and to produce the energy used to power vehicles. However, these emissions can be further reduced by using low-carbon forms of energy, such as renewable electricity.

Approximately 60% of the electricity produced globally is made using fossil fuels (IEA, 2021c). Despite this, direct electrification solutions such as BEVs and ERSVs already produce approximately 40% fewer GHGs than conventional diesel ICEVs over their lifecycle, including emissions from vehicle production and use

and based on the global average carbon intensity of electricity (ITF, 2021a). BEV and ERSV lifecycle emissions are even lower in regions with lower-carbon electricity and stated ambitions to increase the share of renewable electricity, as is the case in Europe and the United States. Similarly, hydrogen FCEVs could significantly reduce GHGs when using hydrogen produced via low-carbon production routes such as electrolysis with renewable electricity. However, almost all hydrogen production today is still made using fossil fuels (IEA, 2019).

Zero-emission vehicles may also improve countries' energy security by reducing dependence on foreign fossil fuels and potentially opening up to a broader range of countries for energy imports. Electricity and hydrogen can be produced using several technologies and in a broad range of environments, potentially offering greater resilience to global energy markets and geopolitical crises than the continued dependence on fossil fuels.

Despite these significant opportunities, there remain a number of important barriers to the adoption of zero-emission vehicles.

Potential challenges for zero-emission vehicles

New, low-carbon vehicle technologies need to be financially competitive with competing technologies to be adopted into the mass market. ZEVs have considerably higher upfront purchase costs than incumbent technologies, which may hinder their adoption by small companies with limited capital. Crucial mechanisms enabling cost reductions include increases in economies of scale and learning-by-doing effects.

A number of potential barriers to adopting ZEVs relate to the operational requirements and possible logistical changes that new technologies may entail. The carrying capacity of both BEVs and FCEVs may be hindered by the weight and volume of their powertrains (e.g. batteries in BEVs and hydrogen storage tanks in FCEVs). Battery charging times may be an additional barrier for BEVs. It is expected that BEVs will primarily rely on overnight depot charging (Borlaug et al., 2021), but any additional electricity needed to meet range requirements would likely need high-power charging. Power ratings of one megawatt, currently under discussion (ITF, 2020), could allow 30- to 45-minute charging times and fit within regulated driver rest periods. However, this may require some adaptation to daily operations and a significant and uncertain deployment of new charging and electricity grid infrastructure in the coming years. Furthermore, high-power charging is likely to be more expensive than depot charging and its costs are dependent on the utilisation of the infrastructure.

An electric road system (ERS) could overcome many of the battery weight, range and charging limitations of BEVs. Vehicles operating on an ERS charge while connected to overhead wires, therefore requiring smaller batteries. Barriers to an ERS relate primarily to the high upfront costs associated with the deployment of the overhead wires, which must be constructed before pantograph vehicles can be adopted. The uncertain timescales associated with the construction of an ERS and subsequent uptake of pantograph vehicles pose significant financial risks to investors due to the unclear utilisation of the asset. This also leads to uncertainty in the fees that users would need to be charged to pay back infrastructure investments.

Additional barriers to ERS relate to ensuring common international standards, allowing for interoperability for trucks travelling across borders (ITF, 2020). Finally, there is uncertainty about how the adoption of BEVs might impact ERS utilisation, both positively and negatively. Other electric road system concepts, including conductive transmission from electric rails on the road surface and inductive transmission from the road,

are also under consideration but are currently at a lower level of technological maturity compared with overhead catenary solutions (Ainalis, Thorne and Cebon, 2020) and are not considered in this report. The numerous barriers to ERS mean strong concerted action is needed from a broad range of stakeholders including vehicle manufacturers, governments, electricity transmission and distribution system operators, road network managers, logistic fleet owners, logistic service providers and users.

Battery swapping stations, which physically replace a truck's discharged battery with a fully charged replacement, could be a solution to managing battery size and avoiding some long-distance range limitations. Large-scale pilot tests of battery swapping solutions for heavy-duty vehicles are currently underway and showing promise in the People's Republic of China (Liu and Danilovic, 2021). Business models associated with battery swapping include offering battery rental services (also known as "batteries-as-a-service"). These could help to reduce upfront purchase costs of electric trucks and shift costs to operational expenditure, which is already comparatively low for electric vehicles. Battery swapping can also avoid high-power charging of batteries since they can be removed from a vehicle and charged at a lower power over longer time periods. This could reduce charging costs and place less stress on batteries, which can improve the longevity of batteries by approximately 20% (Liu and Danilovic, 2021). Current barriers include the standardisation of batteries to allow swapping between different truck manufacturers, safety issues and untested (at scale) business models ensuring high infrastructure utilisation.

Range limitations could also be overcome with hydrogen-powered FCEVs since refuelling times for hydrogen vehicles are expected to be faster than BEV recharging times. However, hydrogen truck concepts using liquefied hydrogen refuelling will require preconditioning that may take longer than simply refuelling diesel (ITF, 2020). Similarly to high-power BEV charging and an ERS, the cost of hydrogen refuelling infrastructure is highly dependent on its utilisation, with uncertainty about how quickly the market will adopt FCEVs. However, the lack of existing low-carbon hydrogen production and widespread hydrogen refuelling and distribution infrastructure means that FCEVs face significant barriers to scaling up and delivering GHG emission benefits in the short term. Finally, the energy efficiencies of FCEVs and hydrogen production from electrolysis are relatively low compared to powering BEVs or ERSVs with renewable electricity. This means that a significantly greater quantity of electricity generation will be needed to fuel FCEVs with hydrogen made from renewable electricity than BEVs, implying higher energy costs (ITF, 2021a).

A number of other vehicle technologies could also play a role in decarbonising heavy-duty road freight, particularly in applications where ZEVs might not be feasible. These include hybrid powertrain solutions and low-carbon fuels used in internal combustion engines, such as biofuels, hydrogen and diesel electrofuels. These technologies are not considered in this report but will be considered in future work. Battery swapping solutions are also not explicitly considered in the analysis.

The role of technology neutrality in policy making

There are many zero-emission technologies and all require appropriate infrastructure to accelerate their adoption. However, policy makers and industry experts remain uncertain about the long-term potential of new technologies, as each has advantages and disadvantages, and their adoption so far has been limited. This uncertainty is potentially compounded for international transport if countries adopt diverging technology pathways. This creates hesitancy to invest for fear of stranded assets.

Technology neutrality is the principle that policy makers do not cater policy to favour specific technologies but create opportunities for innovation to meet society's needs. Policies should target a desired outcome and remain neutral to the technologies used to achieve that goal. In doing so, policy makers avoid picking

winners and closing the door to specific technological pathways and instead leave industry and market forces to choose how to meet targets in an efficient, cost-optimal way. Technologies develop quickly, as does the understanding of their relative pros and cons. Policies that are agnostic about technologies can be resilient to technological change.

However, there are two fundamental limitations to technology-neutral policies:

The first is in an uncertain technological context, where the financial risks are too large for market forces to act alone in adopting new technologies. This is particularly the case when significant infrastructure investments are required. In such cases, a government may be called on to provide support in the form of infrastructure investment. Government budgets are limited, meaning that only a selection of the most promising options can be funded, which can "lock-in" specific technology options.

The second limitation to technology neutrality is in a time-limited context, where market forces alone will struggle to adopt technologies at the speed necessary to meet targets. Meeting aggressive GHG emission reduction targets by 2050 will require additional policy intervention, and remaining agnostic about technologies risks postponing action on decarbonisation. The implications of choosing a technology that helps to reach climate targets but that, in the long term, is not "optimal" may be less severe than not choosing any technology at all, given the looming impacts that climate change will impose upon the global economy.

Technologies develop quickly, and governments are rightfully wary about committing to specific options in an uncertain technological environment. However, are technologies likely to develop quickly enough to make an appreciable difference to the choice of preferred technology, and is it worth postponing decisions? This report aims to shed light on potential technological pathways to help prioritise policy actions and unlock action to promote ZEVs.

The total cost of ownership (TCO) is one of the most important metrics influencing trucking companies' purchase decisions and the adoption of new technologies in the commercial vehicle sector. The TCO is the sum of all expenses over the ownership period of a vehicle and includes vehicle purchase costs, financing, residual value and the cost of operation. This analysis investigates the TCO of the three most prominent zero-emission vehicle technologies for the heavy-duty vehicle sector and compares them to conventional diesel vehicles. The novelty of this analysis is the assessment of multiple vehicle technologies across a wide range of vehicle classes, range requirements and possible futures. Particular emphasis is placed on the uncertainty associated with each technology to answer the following questions:

- Which technologies are most likely to reach TCO parity with conventional diesel vehicles?

- When might TCO parity be reached?

- How does TCO parity differ between vehicle classes and market segments?

- What degree of certainty can be placed in the results? How might further actions by government or industry reduce uncertainty?

Comparing truck technologies in an uncertain future

Global analyses suggest that zero-emission vehicles will likely play a pivotal role in meeting ambitious climate targets (IEA, 2021b), including in heavy-duty road freight. Recent initiatives highlight that action stimulating their adoption is already underway. In 2021, several countries signed a memorandum of understanding pledging to enable 100% of zero-emission medium- and heavy-duty truck sales by 2040 (CALSTART, 2021). Additionally, a number of private-sector companies have announced the initial commercial production of ZEV trucks and the building of charging infrastructure for trucks (Daimler Trucks, 2021; Basma and Rodriguez, 2021; Scania, 2021; Volvo, 2022).

Table 2. European vehicle types as defined by European Union heavy-duty vehicles
CO_2 emission regulation 2017/2400

Vehicle group	Axle type	Chassis	Gross weight (in metric tonnes)	Sales share (2019)	Included in analysis
1	4x2	Rigid/Tractor	7.5-10	1.63%	Yes
2	4x2	Rigid/Tractor	>10-12	4.17%	Yes
3	4x2	Rigid/Tractor	>12-16	4.22%	Yes
4	4x2	Rigid	>16	10.10%	Yes
5	4x2	Tractor	>16	52.25%	Yes
6	4x4	Rigid	7.5-16	1.21%	No
7	4x4	Rigid	>16	1.02%	No
8	4x4	Tractor	>16	0.84%	No
9	6x2	Rigid	All weights	13.77%	Yes
10	6x2	Tractor	All weights	2.86%	Yes
11	6x4	Rigid	All weights	1.93%	Yes
12	6x4	Tractor	All weights	0.57%	Yes
13	6x6	Rigid	All weights	0.53%	No
14	6x6	Tractor	All weights	0.02%	No
15	8x2	Rigid	All weights	0.59%	No
16	8x4	Rigid	All weights	3.85%	No
17	8x6, 8x8	Rigid	All weights	0.43%	No

Sources: Vehicle groups: European Commission (2017); heavy-duty vehicle sales shares: Mulholland et al. (2022).

Heavy-duty vehicles come in a range of sizes to suit a wide spectrum of applications, from urban deliveries to long-haul regional and international travel. The differences between truck types and regions will likely affect the ease of transition to zero-emission powertrain technologies in each market segment. For example, it may be more challenging to electrify particularly heavy vehicles with high-energy requirements or vehicles with long-distance range requirements, than smaller vehicles. To account for these differences, the analysis in this report covers a broad range of heavy-duty road freight vehicles with a gross weight above 7.5 metric tonnes in groups defined by EU CO_2 emissions regulations, shown in Table 2. EU regulations define vehicle groups according to their gross vehicle weight, chassis type (rigid or tractor-trailer) and axle configuration. This analysis only studies vehicles included in EU HDV certification regulation 2017/2400 (European Commission, 2017), as limited data is available for other vehicle groups. Vehicle group 16, which is included in EU regulation 2017/2400, is also omitted due to a lack of data. The vehicle groups included in the analysis accounted for 91.5% of heavy-duty vehicle sales in 2019.

Estimating the total cost of ownership

A growing number of studies have attempted to predict the TCO of trucks with various powertrains. Each study typically creates a future scenario for the TCO of each vehicle powertrain, using several assumptions about the costs of different vehicle components and vehicle performance attributes such as fuel efficiency. Typically, a single class of truck is evaluated across a number of technologies and a number of scenarios. This report explores the TCO of a broad range of heavy-duty vehicle classes in different market segments in Europe and across a wide spectrum of uncertainty.

The TCO of a new vehicle is estimated by adding the capital expenditure (CAPEX) into the purchase of the vehicle with all operational expenditure (OPEX) over a seven-year vehicle ownership period (broadly, the average lifetime of European road tractors estimated from OECD (2022) statistics) and subtracting the residual value at the end of ownership (equation 1 in Annex B). The CAPEX of the vehicle is calculated as the sum of vehicle glider and vehicle component costs such as batteries, power electronics, motors, fuel cells and pantograph. The OPEX of using a vehicle each year is calculated as the sum of energy, operation, maintenance and vehicle financing costs. Other costs such as driver wages, which are common to all powertrains, are omitted, as are road tolls such as the Eurovignette directive and additional policy support measures in the base results. Energy costs include infrastructure costs associated with electric charging, ERS construction and hydrogen refuelling.

Quantifying uncertainty

Developing a scenario for the TCO of a vehicle technology requires making several assumptions about different variables, including the costs of different vehicle components and how they evolve over time. The choices in defining these variables can greatly impact the results, increasing the risk of unintentional bias. While this risk of bias can never be mitigated entirely, it can be significantly reduced by exploring a wide range of possibilities.

Table 3 presents the primary sources of uncertainty considered in this report. For each source of uncertainty, an upper and lower bound is chosen to develop a range of possible future values of each variable based on available academic literature and industry reports. Full details of the uncertainties for each variable are outlined in Annex A.

Table 3. A summary of sources of uncertainty

	Source of uncertainty	Uncertainty type	Lower bound	Upper bound
A	Possible cost reductions in electricity production due to the increasing penetration of low-cost renewable electricity	Time varying range	~2% price reduction per year from EUR 0.125/kWh in 2020 (EUROSTAT, 2022).	Fixed at EUR 0.125/kWh (EUROSTAT, 2022).
B	Variance in future diesel fuel prices due to market fluctuations	Fixed range across all years	Lowest average price between 2010-2019 excluding VAT and other recoverable taxes: EUR 0.95/Litre (OECD, 2020)	Highest average price between 2010-2019 excluding VAT and other recoverable taxes: EUR 1.50/Litre (OECD, 2020)
C	Energy-efficiency improvements to all powertrain types from better aerodynamics, light-weighting, reduced friction and drivetrain improvements	Time varying range	Energy-efficiency improvements of 35% in 2030 and levelling out at a 40%-reduction in 2050 with respect to 2020 levels.	Energy-efficiency improvements of 10% by 2030 and levelling out at 20% by 2050 with respect to 2020 levels.
D	The costs of electric drivetrain components including electric motors, converters, on-board chargers, thermal management and high-voltage systems. These could reduce over time due to economies of scale and technical improvements.	Time varying range	Costs fall from around EUR 170/kW to EUR 110/kW with growing production (based partly on Ricardo and ICCT (2021)).	Costs fall from around EUR 340/kW to EUR 220/kW with growing production (based partly on Ricardo and ICCT (2021)).
E	The cost of hydrogen fuel cells for heavy-duty vehicle use, which could reduce over time due to economies of scale and technical improvements. These cost more than those used for passenger vehicles due to longer life requirements and duty cycles.	Time varying range	Costs fall from USD 323/kW to USD 60/kW by 2050 (based on US DOE (2021b)).	Costs fall from USD 323/kW to USD 176/kW by 2050 (based on US DOE (2021b) without economies of scale.
F	Hydrogen fuel cell energy-efficiency improvements	Time varying range	Fuel cell efficiencies rise from 45% in 2020 to 50% in 2030 and 55% in 2050 (based on US DOE (2019, 2021a)).	Fuel cell efficiencies rise from 50% in 2020 to 62% in 2030 and 66% in 2050 (based on US DOE (2019, 2021a)).
G	The cost of on-board hydrogen fuel tanks could reduce over time due to economies of scale and technical improvements.	Time varying range	Costs fall from around EUR 1 000/kg in 2020 to EUR 526/kg in 2030 reaching EUR 260/kg by 2050 with growing production (based partly on Ricardo and ICCT (2021)).	Costs fall from around EUR 1 600/kg in 2020 to EUR 1 000/kg in 2030 reaching EUR 700/kg by 2050 with growing production (based partly on Ricardo and ICCT (2021)).

H	Hydrogen fuel costs at the pump. This cost comprises refuelling infrastructure costs and hydrogen production, purification, transmission and distribution costs, which could reduce over time with increasing scale of low-carbon production.	Time varying range	Hydrogen costs at the pump fall from EUR 9.50/kgH$_2$ in 2020 (H2live, 2022) to EUR 8.5/kgH$_2$ in 2050 assuming low station utilisation (Rose, 2020).	Hydrogen costs at the pump fall from EUR 9.50/kgH$_2$ in 2020 (H2live, 2022) to EUR 1.5/kgH$_2$ in 2050 assuming high station utilisation and likely subsidies.
I	The average global cost of batteries over time across all applications, including passenger cars and stationary storage (These have historically dropped over time due to economies of scale and technical improvements.)	Time varying range	Average global lithium ion battery pack prices fall from EUR 122/kWh in 2020 to EUR 70/kWh by 2030 and EUR 50/kWh by 2050 (based on BNEF (2021a)).	Average global lithium ion battery pack prices rise from EUR 122/kWh in 2020 to EUR 150/kWh in 2025 (based on BNEF (2021a) and Kim (2022)) then fall to EUR 100/kWh by 2050.
J	Additional costs between batteries used for heavy-duty vehicles (HDVs) compared to the average across all applications (Batteries currently cost significantly more for HDV applications than for passenger vehicles, principally due to smaller production volumes and higher durability requirements.)	Time varying range	HDV battery packs cost 46% more than average passenger car batteries in 2020, then fall in cost to 20% more in 2030 and arrive at parity with average passenger car batteries by 2035 with growing production (based partly on Ricardo and ICCT (2021)).	HDV battery packs cost 146% more than average passenger car batteries in 2020, falling in cost to 66% more in 2030 and arrive at parity by 2050 with growing production (based partly on Ricardo and ICCT (2021)).
K	Energy density improvements to vehicle lithium-ion batteries	Time varying range	Energy densities are 140 Wh/kg in 2020, 220 Wh/kg in 2030 and 250 Wh/kg in 2050 (based partly on Schmuch et al. (2018) and BNEF (2021b)).	Energy densities are 200 Wh/kg in 2020, 260 Wh/kg in 2030 and 400 Wh/kg in 2050 (based partly on Schmuch et al. (2018) and BNEF (2021b)).
L	The average power rating of charging stations available on main roads for high-power charging	Time varying range	Average HDV charger station power evolves from 20 kW in 2020, to 50 kW by 2025, 100 kW by 2030 and 1 MW by 2050.	Average HDV charger station power evolves from 500 kW by 2025 and 1 MW by 2030.
M	The cost of high-power charging infrastructure as a function of the rated power	Range as a function of charger power	Charging costs based on CAPEX of charging station: EUR 1 000 for 20 kW, EUR 50 000 for 100 kW, EUR 170 000 for 350 kW and EUR 300 000 for 1 MW.	Charging costs based on CAPEX of charging station: EUR 3 000 for 20 kW, EUR 70 000 for 100 kW, EUR 240 000 for 350 kW and EUR 700 000 for 1 MW.
N	The cost of electric road system and depot charging infrastructure, estimated based on the costs needed to pay back infrastructure, operation and	Fixed range across all years	EUR 0.05/kWh based on construction costs of EUR 1.1 million/lane-km (Wietschel et al., 2019) and 70% utilisation.	EUR 0.19/kWh based on construction costs of EUR 1.65 million/lane-km (Movares, 2020) and 32% utilisation.

	maintenance costs (assumed to be constant over time).			
O	The costs of pantograph systems for vehicles using an overhead catenary electric road system	Time varying range	Assumed to cost EUR 18 000 per vehicle in early-stage deployment by 2030 (based on Ainalis, Thorne and Cebon (2020)) dropping to EUR 10 000 by 2050 (based on IEA (2017)).	Assumed to cost EUR 28 000 per vehicle in early-stage deployment by 2030 (based on Kühnel, Hacker and Görz (2018)) dropping to EUR 12 000 by 2050 (based on Ainalis, Thorne and Cebon (2020)).
P	The residual value of vehicles and batteries, as a percentage of initial capital expenditure	Fixed range across all years	Residual value 20% of initial CAPEX for vehicle, 5% for battery.	Residual value 35% of initial CAPEX for vehicle, 20% for battery.

Note: Full details of assumptions available in Annex A. Lower and upper bounds limit the range of uncertainty considered for each variable. The letters in column 1 of this table correspond to those in Figure 1.

Each variable is used in a numerical model to estimate the TCO of each powertrain and how it changes over time until 2050. Importantly, this analysis takes a possibilistic rather than a probabilistic approach. The aim is to explore a range of possible scenarios without necessarily attributing specific probabilities to their occurrence. For example, this analysis cannot predict the probability of a certain technology reaching cost parity with conventional diesel vehicles in a given year. Instead, it can suggest that a certain percentage of the 1 000 scenarios explored between conservative and optimistic bounds reach cost parity in a given year. The GHG emissions produced by trucks are not considered here and will be the subject of future research. Figure 1 presents the main variables explored in this analysis with estimates of their uncertainty.

Figure 1. Uncertainty ranges of model inputs
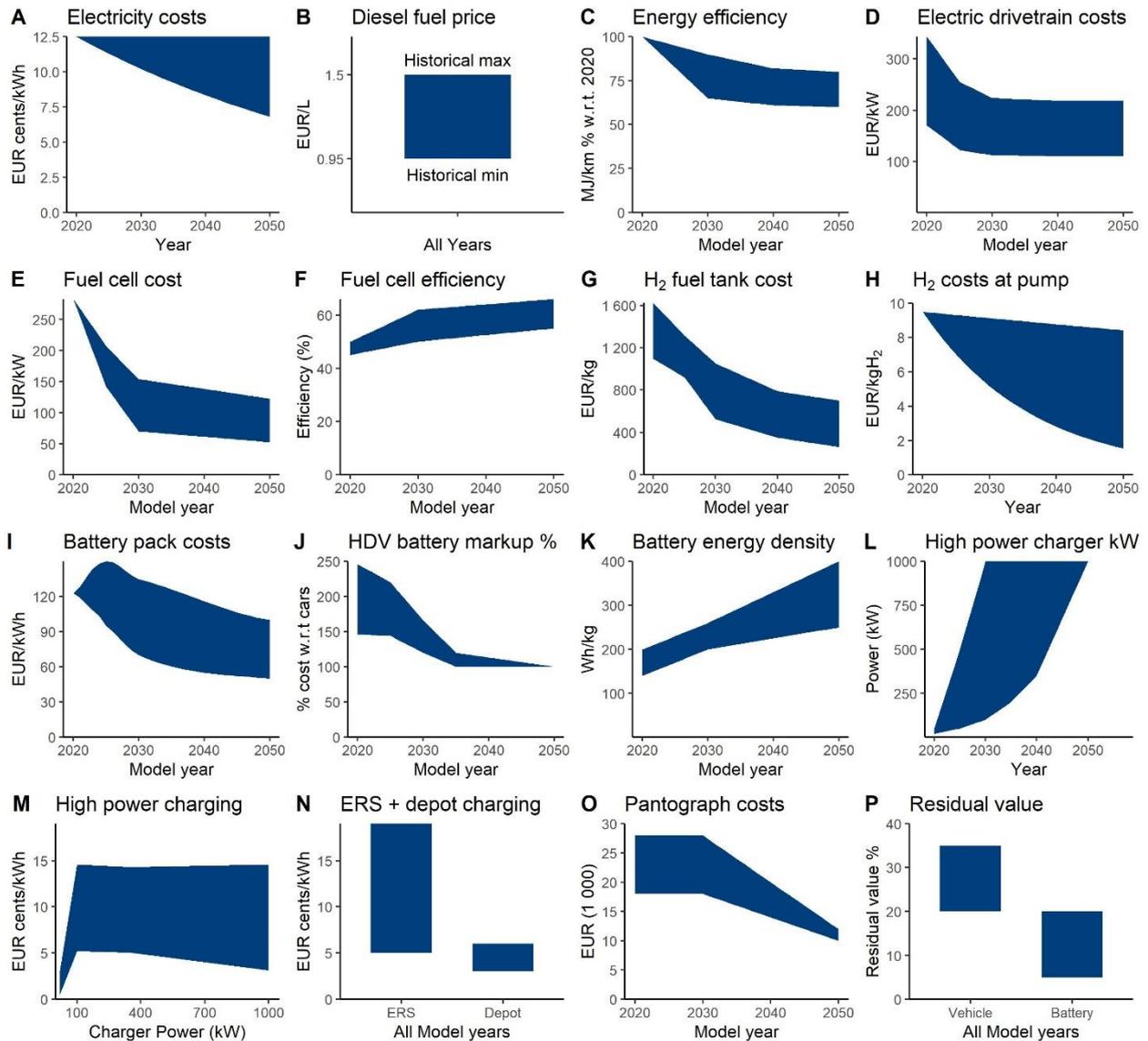
Note: A. Electricity costs reductions; B. Diesel fuel price; C. Energy-efficiency improvements to all powertrain types; D. Electric powertrain costs (motors, inverters, thermal management); E. Fuel cell cost; F. Fuel cell efficiency; G. Hydrogen fuel tank cost; H. Hydrogen fuel costs at the refuelling station pump; I. Average global Lithium-ion battery pack costs; J. Additional costs of heavy-duty vehicle battery packs per kWh compared with passenger car batteries; K. Battery pack energy density; L. Average power capacity of charging stations available on main roads for high-power charging; M. Cost of charging needed to pay back charger infrastructure deployment as a function of charger power capacity; N. Electric road system and depot charging infrastructure costs; O. Range of vehicle pantograph system costs; P. Residual value of vehicles and batteries after seven years of use. Full details for all assumptions are available in Annex A. "Model year" refers to the year a vehicle is sold, rather than the years it is used. "w.r.t": with respect to.

The impact of uncertainty on total cost of ownership

In this analysis, the TCO is estimated over time for trucks in each vehicle group and powertrain combination and for different annual mileage and range requirements within each group. Full details of the assumptions included in the model are available in Annex A.

In 2020 (the base year in this analysis), a newly purchased conventional ICE diesel vehicle remained the most cost-competitive technology option, with the lowest TCO over a seven-year lifetime and uncertainty driven particularly by diesel fuel prices and annual mileage. However, with expected technological improvements and cost reductions in various components from economies of scale, the TCO of ZEV can reduce over time and overlap with conventional diesel vehicles. Figure 2 shows the range of TCOs for European vehicle groups 4, 5 and 9, which are the groups with the highest sales shares (10%, 52% and 14% of sales respectively, see Table 2).

Figure 2. Total cost of ownership with uncertainty: Three European vehicle groups using four different powertrains
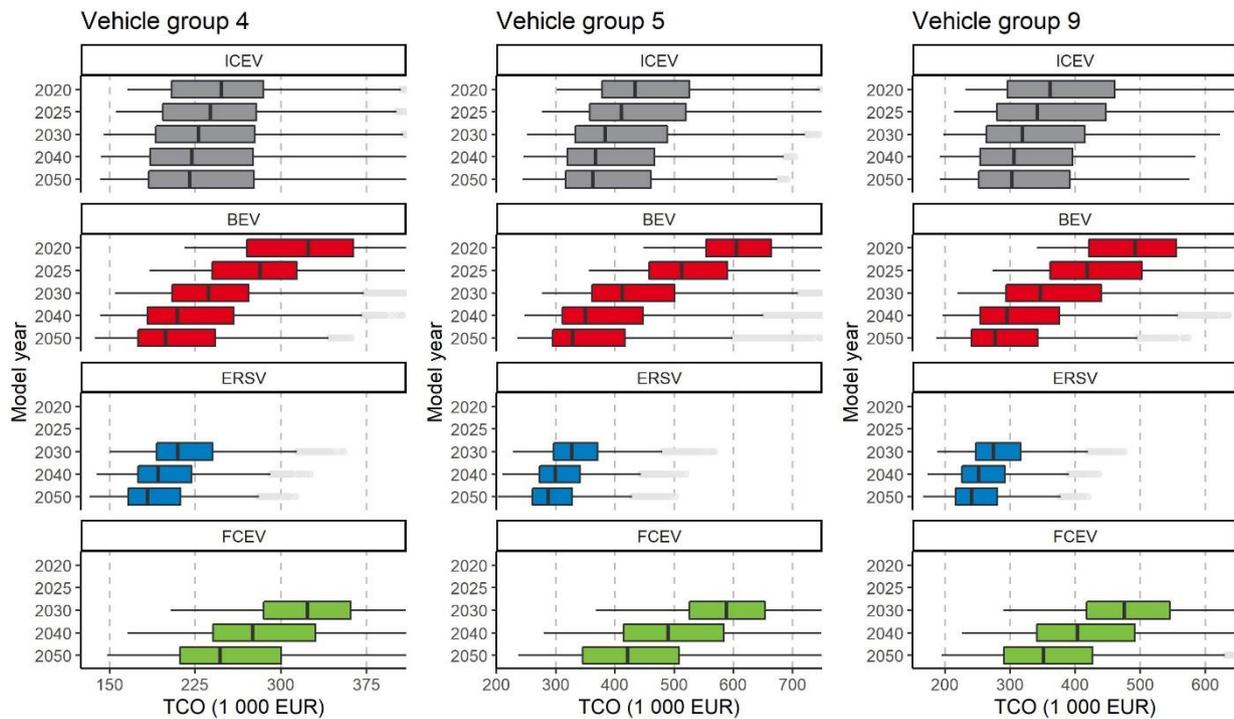
Notes: Range of total cost of ownership (TCO) for vehicle group 4 (rigid 4x2 vehicles), group 5 (4x2 tractors) and group 9 (rigid 6x2 vehicles), based on uncertainty in input variables and between varying range requirements. TCOs for electric road system vehicles (ERSV) and fuel cell electric vehicles (FCEV) are not plotted before 2030 as mass-market uptake is unlikely given the lack of enabling infrastructure. BEV= Battery Electric Vehicle, ICEV= Internal Combustion Engine Vehicle. The black line in each boxplot denotes the median scenario, box edges denote the 25th and 75th percentiles and horizontal black lines are 5th and 95th percentiles of the multiple scenarios explored. Vehicle groups are those defined by the European Commission (2017).

BEVs have relatively high upfront purchase costs and low operational costs compared with ICEVs. The high capital costs are principally due to the cost of a large battery. BEVs have low operational costs because they are far more energy-efficient than other powertrain types and can use relatively cheap energy when using low-power overnight charging. They also have lower maintenance costs due to reduced mechanical

complexity and are therefore likely to have a higher residual value (Hunter et al., 2021), particularly given similar trends in passenger vehicle segments (Guo and Zhou, 2019).

Two factors could make the TCO of BEVs cost-competitive with ICEVs. First, purchase prices could be reduced with economies of scale in battery and powertrain component costs. Second, further improvements in energy efficiency and battery energy density could increase vehicle maximum range capabilities and allow BEVs to avoid high-power charging on main roads. These trends mean that the low operational costs over the lifetime of BEVs could more than compensate for the higher initial investment.

ERSVs can have a similar TCO to BEVs. ERSVs could have smaller battery requirements, which reduce upfront purchase costs (explained further in Annex A). They could possibly face slightly higher energy costs if their primary source of electricity is from overhead catenary wires rather than cheaper, low-power overnight charging. However, this depends partly on the costs of any potential grid upgrades, and the degree to which they are passed on to consumers. Additionally, for countries with a high share of solar electricity, overnight electricity delivered through low-power depot chargers is not necessarily cheaper than day-time electricity delivered through high-power charging or an ERS.

FCEVs also have high upfront purchase costs due to the fuel cell system and hydrogen storage tanks. The TCO of FCEVs is dominated by the cost of hydrogen fuel, particularly in the early years. Future hydrogen fuel costs are particularly uncertain, leading to a wide range of possible ownership expenses. The uncertainty in hydrogen costs substantially affects the future TCO of FCEVs because FCEVs are less energy-efficient than BEVs. In general, the ownership costs of vehicles with energy-efficient powertrains are more resilient against energy price fluctuations.

The impact of uncertainty on technologies' cost-competitiveness

Some factors influencing the range of uncertainty of different powertrain technologies are unique to the technology (e.g. uncertainty in hydrogen costs only affects FCEVs), while others affect a number of technologies (e.g. electric drivetrain costs affect all ZEVs). To understand which new powertrain technology has the lowest TCO each year, this analysis compares 1 000 unique scenarios exploring the full spectrum of uncertainty in input variables across technologies, vehicle groups and daily mileage requirements. The lowest cost powertrain technology in each year is selected for each vehicle group and daily mileage requirement in each scenario.

The uncertainty explored in this analysis includes both favourable and conservative scenarios for each particular technology. The exact date that a technology reaches cost parity with ICEVs is based on the unique combination of input assumptions in each scenario and its probability of occurrence is inherently subjective. The aim of this analysis is to highlight the *range* of years in which each technology may (or may not) reach cost parity with ICEVs across a large number of unique scenarios in an attempt to reduce the level of subjectivity.

Figure 3 consolidates all scenarios across all HDV vehicle groups and excludes electric road systems (which are included in the following section) to show the share of the HDV market that each technology could theoretically attain by having the lowest TCO in each year. This omits considerations about model availability and the infrastructure to support the adoption of new technologies, both of which will prevent the adoption of ZEVs initially. However, it paints a picture of the potential cost-competitiveness of each technology in the future.

Figure 3. Potential sales shares of lowest total-cost-of-ownership technology accounting for uncertainty (excluding ERSVs)
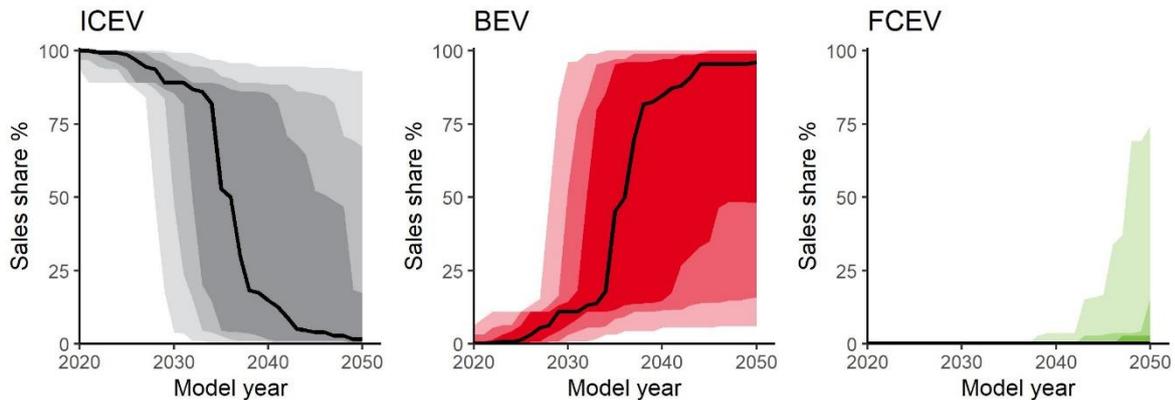
Notes: Black line denotes the median scenario, shading denotes 50th, 75th and 95th confidence intervals of the multiple scenarios explored. Electric road systems are excluded from this analysis.

Figure 3 shows that BEVs are most likely to reach TCO parity with ICEVs between 2020 and 2040. In the median scenario, 80% of vehicle sales could be cost competitive with ICEVs by 2037 without policy intervention. While the majority of scenarios explored point to BEVs rapidly becoming cost-competitive, some scenarios are driven by more conservative input variable combinations and see a more gradual uptake in BEVs. These include scenarios with low diesel prices, high battery prices and slow reductions in electricity costs. Furthermore, there may remain a share of approximately 10% of vehicles for which diesel ICEVs remain the most cost-competitive into the future without any additional policy support.

The results suggest that, for the vehicle categories investigated, FCEVs are unlikely to be able to compete economically with BEVs or ICEVs. This is primarily due to their high upfront purchase costs (which are similar to those for BEVs) combined with relatively high energy costs. In a number of edge cases, with hydrogen fuel costs below EUR 2.5/kgH$_2$ and conservative scenarios for other technologies, FCEVs could be adopted in certain segments. However, in 90% of the scenarios explored FCEVs do not attain more than 10% market share before 2050. This analysis investigates the mass market vehicle categories used in road freight. It is possible that FCEVs could be the preferred technology in relatively niche use-cases not considered in this report (e.g. heavy-duty 70-tonne applications or vehicles used in construction).

Figure 4A shows the year of TCO parity between BEVs and ICEVs by vehicle group and daily mileage percentile. It highlights that BEVs in vehicle groups 1, 2 and 3 are likely to reach TCO parity with ICEVs first. These vehicles have relatively low range requirements, leading to manageable battery costs and a limited need for high-power charging. This means they are likely to be cost-competitive with ICEVs in the short term. Larger vehicle groups without excessively high range requirements are likely to follow.

Vehicles with higher daily mileage tend to have an earlier TCO parity year than vehicles driven short distances, despite the larger battery requirements. This is because OPEX account for a relatively high share of the TCO, meaning the low energy costs of BEVs compared with ICEVs can more than offset the cost of additional battery capacity. The exception to this rule is for vehicles with particularly large daily mileage requirements such as vehicle groups 5 and 9 driven over 1 000 km per day. In these cases, more expensive high-power charging and opportunity costs increase the TCO. The majority of BEV trucks are likely to be cost-competitive with ICEVs before 2040. Some truck segments with low average daily mileage have much greater uncertainty in reaching TCO parity with ICEVs and, in some scenarios, are never cost-competitive with ICEVs before 2050.

Figure 4. Year in which BEVs and FCEVs reach total cost of ownership parity with ICEVs by vehicle group and daily mileage percentile
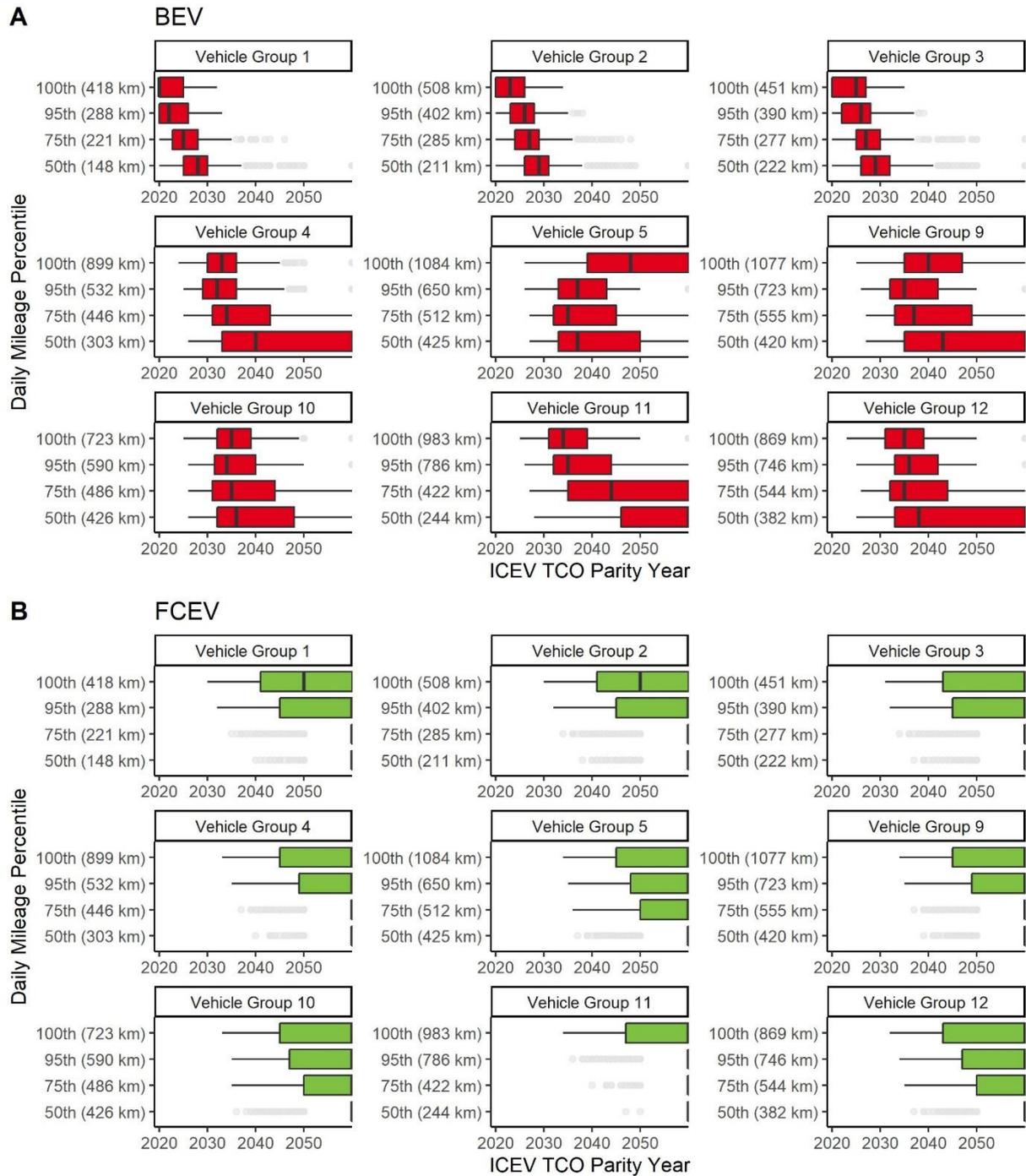
Notes: TCO parity year is the year that the TCO of BEVs or FCEVs is equal to or less than that of ICEVs. Boxplots show the range of uncertainty from input variables in Figure 1. The black line in each boxplot denotes the median scenario, box edges denote the 25th and 75th percentiles and horizontal black lines are 5th and 95th percentiles of the multiple scenarios explored. Daily mileage percentiles show the different daily mileage within each vehicle group (further details are available in Annex 1: Methodology). For example, 50% of group 1 vehicles travel less than 148 km per day on average and all of group 1 vehicles travel less than 418 km per day on average. Vehicle groups are those defined by the European Commission (2017).

Figure 4B shows the year of TCO parity between FCEVs and ICEVs by vehicle group. It shows that FCEVs can be cost-competitive with ICEVs under certain scenarios for vehicles with high daily mileage requirements where, similarly to BEVs, the lower operational costs can present an advantage compared with ICEVs. For vehicles without high daily mileage, this operational cost advantage is insufficient to offset higher purchase costs. This highlights the importance of considering different vehicle use cases and range requirements when comparing HDV technologies.

A comparison of figures 4A and 4B highlights that BEVs are likely to reach TCO parity earlier than FCEVs in most of the applications explored in this analysis. In a limited number of scenarios, FCEVs could compete with BEVs in groups 5 and 9 travelling over 1 000 km per day. However, the lack of cost-competitiveness across the majority of the European market means achieving the economies of scale in vehicle production necessary to bring down vehicle purchase prices and ensure high utilisation of refuelling infrastructure is likely to remain a challenge for these use cases.

Figure 5 shows the share of the heavy-duty vehicle market for which ERSVs could be the lowest TCO technology, assuming that ERS infrastructure is available (the deployment of ERS infrastructure is not explicitly investigated in this analysis). ERSVs could be adopted progressively with the construction of ERSs but would be unlikely to reach mass-market adoption before the mid-2030s. For example, Ainalis, Thorne and Cebon (2020) have estimated the construction of a complete ERS to take approximately eight years.

In the majority of the scenarios explored, ERSVs are more cost-competitive than BEVs when initially introduced in the 2030s. Furthermore, ERSVs have the advantage of lower upfront vehicle purchase costs than large-battery BEVs. The lower initial cost may encourage truck operators' adoption of ERSVs and stimulate the technology's more rapid introduction into the vehicle fleet, resulting in rapid CO_2 emissions reductions (although this is not modelled in this analysis). However, the utilisation of ERS infrastructure is a major source of uncertainty.

Figure 5. Potential sales shares of electric road systems vehicles with uncertainty
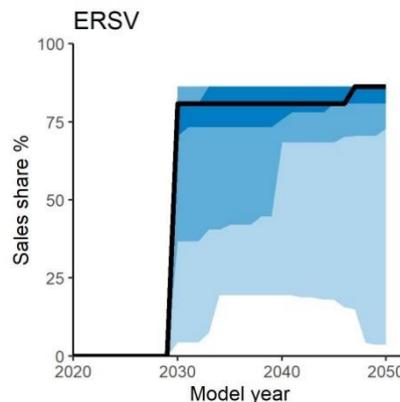
Notes: Black line denotes the median scenario, shading denotes 50th, 75th and 95th confidence intervals of the multiple scenarios explored. ERSV are only introduced into the mass market in 2030 post-construction of overhead lines on main roads.

The ERS design explored in this analysis is prone to risks. The ERSVs have a small battery to cover the distance between depot and motorway and then use overhead wires for the majority of electricity consumption. If too many trucks choose to source their electricity from cheap depot charging, the utilisation of overhead catenary wires could drop and lead to higher ERS charging costs. The rise in cost, in turn, could produce a vicious cycle of low ERS utilisation and stranded assets.

However, alternative configurations may be possible. For example, if ERS were used to charge ERSVs' batteries (rather than just maintain the state-of-charge), the higher flow of energy could cut the cost of using the overhead catenary equipment per unit of energy. These "charging corridors" could be a cost-competitive substitute for high-power stationary charging. This and other plausible variations make it uncertain whether BEVs or ERSVs will dominate the market. Further research and pilot tests, such as those under consideration in Germany and the UK (BMVI, 2021; UK DfT, 2021), may help to clarify additional costs or barriers to either solution.

One significant variable determining the cost of an ERS is the assumed payback period, here assumed to be 35 years, broadly similar to other long-lasting government-funded infrastructure. Halving this payback period would decrease the potential market share of ERSVs to roughly 40% of the market. This highlights the importance of financing and suggests significant government support would likely be needed for it to be viable.

This analysis tracks the lowest-cost powertrain over time as soon as it becomes cost-competitive on a TCO basis. However, it cannot account for all real-life situations. Imperfect knowledge, behavioural factors, additional costs or incentives, or a lack of enabling infrastructure deployment or production capacity of new vehicle powertrain technologies may mean that the real-world adoption of ZEVs into the vehicle fleet will take longer than projected.

Given the urgent need to counter climate change, the opportunities for lower-cost logistics and reduced energy demand for fossil fuels, further policy measures could help strengthen the case for adopting ZEVs and are examined in the following section.

Policy measures can pave the way for zero-emission vehicles

Since some ZEV technologies have the potential to be cost-competitive with conventional ICEVs in the near future, introducing regulations to stimulate their adoption is likely better than introducing financial incentives. However, financial incentives and other economic measures could encourage industry to develop effective ZEV technologies more quickly, therefore making them cost-competitive with ICEVs earlier and accelerating GHG emissions reduction. Economic measures can also help to address equity challenges in the uptake of new technologies.

Figure 6 shows the effects of three example policy measures to further incentivise the adoption of BEVs with respect to baseline scenarios, excluding FCEVs and ERSVs. In the baseline, the median scenario suggests that BEV trucks could be cost-competitive with ICEVs in 50% of annual European truck sales by 2035. (BEV costs would be marginally higher than ICEVs in the remaining 50% of the market, which includes particularly challenging road freight applications.) Vehicle financing costs are higher for ZEVs than conventional diesel trucks, given their higher upfront purchase costs. Offering government-backed loans with a 0%-interest rate to truck operators purchasing a BEV (rather than the assumed baseline case of 3% interest) could accelerate the adoption of BEVs in all vehicle groups by approximately six years compared with the baseline.

Similar results could be achieved by offering purchase incentives of approximately EUR 20 000 per vehicle on new purchases of BEVs (assumed to be fully passed on to consumers). These policy measures could allow even the most challenging vehicle groups to be cost-competitive with ICEVs by the mid-2030s.

Introducing a carbon tax of EUR 100/tonne of CO_2 on diesel fuel, equivalent to approximately EUR 0.25/litre of diesel, would have an even greater effect, allowing BEVs to be cost-competitive in more than half of heavy-duty truck sales by 2028.

Notably, all three policy measures would shift the range of uncertainty on the TCO of trucks to earlier years. Their introduction could unlock edge-case possibilities of TCO parity between BEVs and ICEVs in most vehicle segments in the mid-2020s. Furthermore, combining policy measures could be revenue-neutral: for example, the revenues from carbon taxes could be used to fund low-interest-rate loans or purchase subsidies.

These policy measures should be time-limited and would only be necessary to accelerate the deployment of ZEVs until economies of scale, efficiency improvements and battery cost reductions allow ZEVs to compete with ICEVs without further policy support, which baseline scenarios suggest is possible.

Figure 6. The impact of policy measures on adoption of BEVs (excluding ERSVs and FCEVs)
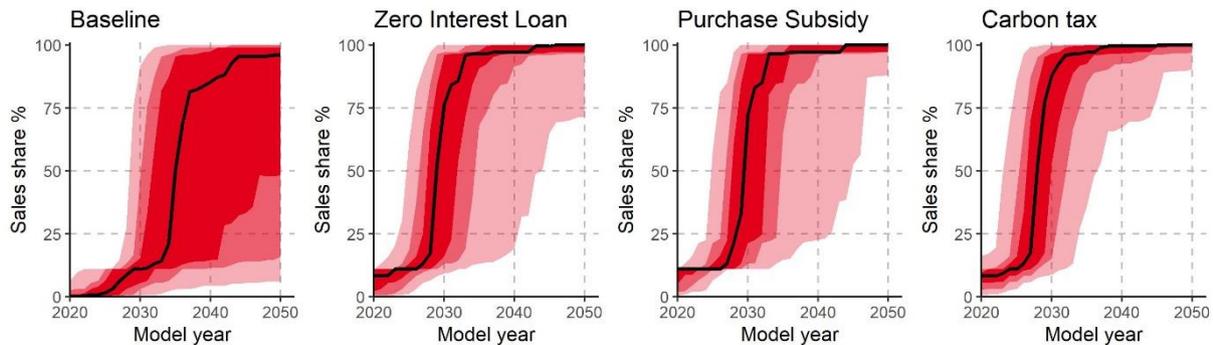
Notes: Black line denotes the median scenario, shading denotes 50th, 75th and 95th confidence intervals of the multiple scenarios explored. Baseline results are the same as those presented in Figure 3 and exclude ERS. Zero-percent interest loans set financing costs of BEVs to zero assuming 0% interest rates rather than the default 3%. Purchase subsidy includes a EUR 20 000 incentive for BEVs compared with ICEVs. Carbon tax includes an additional cost to diesel fuel from a EUR 100/tonne CO_2 price.

Some of the most important measures needed for the adoption of ZEVs involve stimulating the construction of charging and refuelling infrastructure, including necessary electricity grid upgrades. Without the necessary infrastructure, the adoption of ZEVs will not be possible. The timescales and market dynamics of the adoption of ZEV recharging and refuelling infrastructure are not explicitly modelled in this analysis. Nonetheless, there are important differences in the barriers to infrastructure roll-out between the three ZEV technologies explored in this report.

For BEVs, there is already a substantial roll-out of charging infrastructure for passenger cars that truck operators and manufacturers may be able to leverage. Deploying charging infrastructure can be incremental due to the relatively low cost of individual charging stations. Additionally, chargers can be installed on private property with relative ease, giving truck operators greater power of adopting BEVs into their fleet. Conversely, infrastructure for ERSVs and FCEVs is much more likely to require concerted government support since both require larger initial investments, with greater associated risk, to ensure a sufficiently large infrastructure network for the purchase of vehicles to make sense. An underexplored topic is whether such strong policy initiatives could help to roll out the required infrastructure for ZEVs faster than the individual adoption of BEV depot chargers by small trucking companies.

Conclusions

Zero-emission vehicles are set to be cost-competitive with conventional ICEVs before 2040 without policy support. They will be competitive in all vehicle size segments, ranging from the smallest 7.5-tonne rigid trucks to the largest 40-tonne tractor-trailers. However, the year that ZEVs become cost-competitive with ICEVs varies by size segment and daily mileage needs. The smallest vehicles, with high daily mileage and a reliance on depot charging, already had the potential in 2022 to reach TCO parity with diesel vehicles in the range of futures considered in this analysis. Larger vehicle size segments, which typically travel longer distances, are likely to be cost-competitive with ICEVs by around 2037 without policy support.

BEVs and ERSVs have the greatest promise to be cost-competitive with conventional diesel ICEVs in the European vehicle segments explored in this analysis. This is predominantly due to their higher energy efficiencies, which keep operational costs low and offset higher upfront purchase costs. Further detailed assessments of the relative merits of BEVs and ERSVs are needed to understand which technology can offer the most significant financial and CO_2 emissions savings, while accounting for real-world constraints. Technology-neutral policies that avoid closing the door to either technology are warranted until it is clear that policy objectives (e.g. GHG emission reductions) could be better achieved by one over the other.

In the wide range of uncertainty explored in this analysis, hydrogen FCEVs are not able to compete significantly with other vehicle technologies. FCEVs would only be cost competitive in a small number of edge cases, with highly ambitious hydrogen fuel costs below EUR 2.5/kgH$_2$ (at the pump) and conservative scenarios for other technologies. This lack of cost-competitiveness across the majority of the European market means that achieving the necessary economies of scale in vehicle production to bring down vehicle purchase prices and ensure high utilisation of refuelling infrastructure is likely to remain a challenge for FCEVs.

Policy measures are essential to help accelerate the adoption of ZEVs. Effective measures include purchase subsidies, carbon taxation and low-interest-rate loans to reduce vehicle financing costs associated with vehicle purchase. These policies would help shift the range of uncertainty on the adoption of ZEVs, kick-starting economies of scale of production and opening possibilities for ZEVs to be competitive with diesel vehicles before 2030.

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Annex A. Methodology

This section includes details about the modelling and input assumptions. The analysis draws from recent reports published by Ainalis, Thorne and Cebon (2020), Basma, Saboori and Rodríguez (2021), Hunter et al. (2021) and Ricardo and ICCT (2021) and builds on them with additional data sources. The novelty of the present report is that it examines how the uncertainty in underlying variables affects the total cost of ownership (TCO) and rates of adoption of zero-emission vehicles (ZEV) in multiple market segments and across three ZEV technologies: battery electric vehicles (BEV), electric road system vehicles (ERSV) and fuel cell electric vehicles (FCEV).

Vehicle energy efficiency

The fuel efficiency of each vehicle group and powertrain configuration is estimated over a range of speeds and accelerations, known as a drivecycle, to approximate conditions during real-world driving. Each vehicle is simulated over three drivecycles (urban delivery, rural delivery and long-haul delivery) used for fuel economy testing regulations in the European Union (as part of the VECTO modelling suite). Each simulation is used to determine road load forces (aerodynamic, inertia, gravitational and friction forces) for each vehicle and powertrain type over each drivecycle with a methodology that is similar to that of Gaete-Morales et al. (2021). For each European vehicle group, frontal area, aerodynamic drag coefficient, friction coefficient, vehicle mass and payload are sourced from default VECTO model inputs (European Commission, 2021b). Adding an additional 1 000 kg of weight (for example from a particularly large battery) to a group 5 vehicle adds approximately 2% to its energy use per kilometre. Road loads are converted into vehicle energy requirements using average powertrain energy efficiencies for diesel vehicles, BEVs and FCEVs and are calibrated with VECTO outputs for conventional diesel vehicles for each drivecycle (EEA, 2021). VECTO results for ZEV powertrain vehicles are not yet available so could not be used for calibration. BEVs are assumed to have a powertrain energy efficiency of 90%. The electric charging efficiency of BEVs and ERSVs is assumed to be 95% (Burges and Kippelt, 2021). ERSVs are assumed to have the same energy efficiency as BEVs.

The energy efficiency of FCEVs are calculated by dividing the energy efficiency of an equivalent BEV by average efficiency of a fuel cell. Given their limited deployment to date, there remains significant uncertainty about expected improvements in fuel cell energy efficiencies. Upper and lower bounds are chosen to account for this uncertainty and shown in Figure 1F. US DOE (2021a) estimates peak (rated) efficiencies of fuel cells to be 54% in 2020 with targets to reach 68% in 2030 and an "ultimate" target of 72% peak efficiency (US DOE, 2019). Average fuel cell efficiencies during use are lower than these peak efficiencies and are assumed to be between 45-50% in 2020, rising to between 50%-62% in 2030 and 55-66% efficient in 2050.

The average energy efficiency in typical operations for each truck type and powertrain is included in Table 4. These are estimated by weighting the fuel consumption over each drivecycle using the shares. Future incremental energy-efficiency improvements to all trucks from improved aerodynamics, powertrain efficiencies and light-weighting from the base year are estimated between a lower bound with energy-efficiency improvements of 35% in 2030 and levelling out at a 40% reduction in 2050 with respect to 2020 levels. An upper bound assumes efficiency improvements of 10% by 2030 and 20% by 2050.

Table 4. Energy efficiency (in 2020) by powertrain, drive cycle allocation and vehicle group

Vehicle Group	Energy Efficiency (MJ/km)				Drive cycle allocation			Vehicle weight (kg)		
	BEV	ERSV	FCEV	ICEV	RD	LH	UD	GVW	ICEV powertrain	Max battery
1	1.75	1.75	3.82	6.45	40%	0%	60%	8 800	1 189	1 949
2	1.89	1.89	4.08	6.51	50%	0%	50%	22 500	1 453	2 213
3	2.21	2.21	4.84	7.89	50%	0%	50%	15 500	1 525	2 285
4	3.13	3.13	6.29	7.74	68%	27%	5%	19 000	1 654	2 414
5	5.26	5.26	10.34	12.07	12%	88%	0%	40 000	2 246	3 006
9	4.12	4.12	8.18	9.65	43%	57%	0%	27 000	2 142	2 902
10	5.36	5.36	10.54	12.3	10%	90%	0%	40 000	2 426	3 186
11	3.58	3.58	7.33	8.92	100%	0%	0%	30 000	2 468	3 228
12	5.28	5.28	11	13.57	100%	0%	0%	40 000	2 562	3 322

Notes: BEV: battery electric vehicle; ERSV: electric road system vehicle; FCEV: fuel cell electric vehicle; ICEV: internal combustion engine vehicle (diesel); RD: regional delivery; LH: long haul; UD: urban delivery; GVW: gross vehicle weight. Vehicle groups are those defined by the European Commission (2017).

The fuel efficiency of FCEVs degrades substantially over the course of their life due to catalyst poisoning. In this analysis, fuel economy degradation in line with DOE future targets of 20% reduction in fuel economy after 25 000 hours of operation is assumed (US DOE, 2021b) and estimated using equation 2 in Annex B. Fuel cell replacements are not considered since the use of a FCEV for approximately 10 hours per day, 270 days per year over a seven-year lifetime is below the US DOE target lifetime of 25 000 hours.

Vehicle technical characteristics, annual mileage and range requirements

This section includes details of vehicle technical specifications and annual mileage and range requirements.

Figure 7. Vehicle purchase cost, engine power and average range requirements
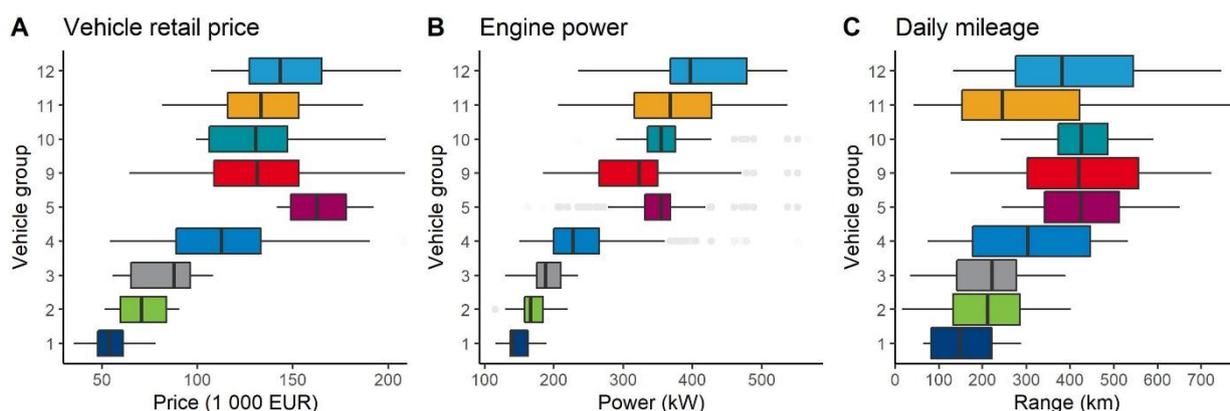
Notes: A: Vehicle retail price estimated using data from TuttoTrasporti (2022); B: Rated diesel engine power, sourced from EEA (2021); C: Range requirements are calculated based on annual mileage in the first year of use. Vehicle groups are those defined by the European Commission (2017).

Engine Power

Median engine power for each vehicle group is shown in Figure B and is sourced from vehicle type approval test data (EEA, 2021). Findings from vehicle simulations performed by Hunter et al. (2021) suggest that differences in engine power requirements between ZEV powertrains are relatively minor. For simplicity, power requirements for BEV, ERSV and FCEV powertrains are therefore assumed to be similar to those of conventional diesel vehicles in each vehicle group.

Annual mileage and range requirements

Important factors affecting the TCO of a vehicle are the assumed annual mileage and range requirements. Trucks differ in their operational requirements and environments, with different annual mileages based on the application. Furthermore, the average annual mileage of trucks decreases as they age, with vehicles typically being driven the most when they are new. To account for this diversity, each vehicle group is evaluated over a wide range of annual mileage distributions. Annual mileage requirements for each vehicle group are estimated using publicly available information on used vehicle sales from www.Truck1.eu, www.Gratka.pl and www.Mascus.co.uk. Knowing the vehicle cumulative mileage and age of different types of vehicles, a cubic function was fitted to the data using quantile regression to estimate how cumulative mileage grows with the vehicle age across each percentile and vehicle group. By taking the derivative of the fitted cubic functions, a quadratic function representing annual mileage as a function of vehicle age could be estimated for each vehicle group and percentile (plotted in Figure C).

Figure 8. Annual mileage by vehicle group
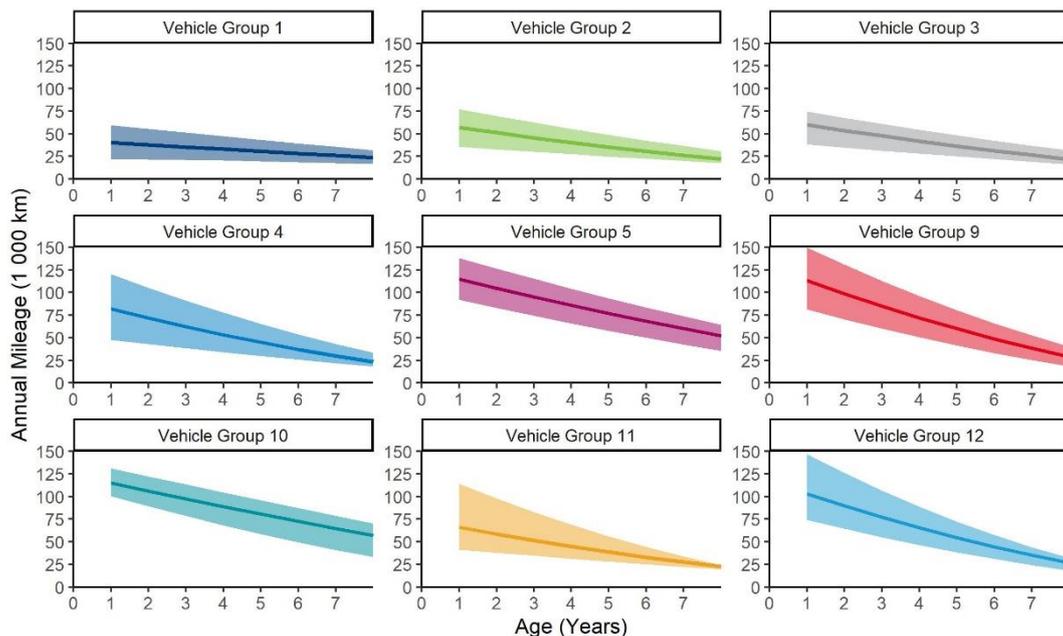
Notes: Figure shows the median annual mileage of each vehicle group (solid line); shaded areas are between the 25th and 75th percentiles. Vehicle groups are those defined by the European Commission (2017).

Finding publicly available information on vehicle range requirements for different trucks is challenging. In this analysis, range requirements are estimated based on the first year of use (which is typically where maximum annual mileage occurs). The annual mileage distributions from the first year of use (Figure) are divided by annual days of operation to approximate vehicle daily use. Data from Scania for European 4x2

group 5 tractors during their first year of use (Wentzel, 2020) is compared with second-hand vehicle sales data and alignment is achieved when assuming the annual usage of European trucks to be approximately 270 days/year. This is similar to survey data in the United States, which found the median annual usage of trucks to be approximately 260 days/year (Lutsey, 2008). Range requirement distributions are then estimated for each vehicle group assuming the same number of days of use and are shown in Figure C.

Battery size, hydrogen storage requirements and gross vehicle weight limits

The mass of trucks on the road is regulated to ensure safe operating conditions. Regulations include specific weight limits – for both the vehicle and its payload – based on the number of axles. BEVs with long-distance range requirements may need a large and heavy battery, limiting maximum payload capabilities and negatively affecting operational feasibility. This is less likely for FCEVs and ERSVs, which are expected to need smaller battery sizes than BEVs. The European Commission recognised the risk of operational limitations to ZEVs from heavy batteries and recently passed regulations allowing ZEVs to operate with an additional two tonnes of weight (EU, 2019). This analysis assumes that the payload capabilities of trucks must remain unchanged from conventional diesel vehicles. Therefore, the weight of BEV batteries and powertrain must not exceed the sum of the weight of a conventional diesel powertrain and the additional two-tonne regulatory allowance. The weight of conventional diesel and BEV powertrains in each vehicle group is estimated using industry and literature data (Mareev, Becker and Sauer, 2018; Ricardo and ICCT, 2021; Mercedes-Benz, 2021) and is shown in Table 4.

A key factor influencing the weight of batteries is their energy density (the amount of energy per kg of battery). Battery energy density differs by battery chemistry and is continuing to improve over time, with better technologies and cell production methods, which are driving significant reductions in the weight of BEV batteries per kWh. A range of energy densities are used in the analysis to account for the uncertainty in battery chemistries and future improvements, shown in Figure 1K. Energy densities in year 2020 are assumed to be between 140 Wh/kg and 200 Wh/kg (Basma, Saboori and Rodríguez, 2021; BNEF, 2021b). Average pack energy density has doubled over the past decade (BNEF, 2021b). Energy densities are assumed to continue at a similar rate reaching between 220 Wh/kg and 260 Wh/kg by 2030. Energy densities in 2050 are highly uncertain, partly due to the unknown adoption of advanced technologies such as novel solid-state batteries (Schmuch et al., 2018), and are assumed to range between 250 Wh/kg and 400 Wh/kg.

It is assumed that BEVs are fitted with sufficient battery capacity to satisfy daily range requirements (as shown in Figure C). In this analysis, different range requirements for each vehicle group are investigated. For example, 50% of vehicle group 5 tractor-trailers are driven less than 435 km per day on average; it is therefore assumed that a BEV with 435 km-range capabilities could satisfy the requirements of half the vehicle group 5 tractors without any charging en-route. Similarly, approximately 5% of group 5 tractors travel over 650 km on an average day, meaning a particularly large range would be needed for these vehicles to avoid stopping to recharge during the day. The 50th, 75th, 95th and 100th percentiles of average range requirements are investigated for all vehicle groups.

The effective battery capacity required (in kWh) is calculated by multiplying the daily range requirements of each truck by its energy efficiency. An additional 20% of battery capacity is added to this effective battery size to account for oversizing to ensure battery longevity over the vehicle's life. However, if the size of the battery means the vehicle mass overshoots the maximum permissible vehicle weight, or an arbitrary limit of 1 MWh, then battery capacity is limited to the size needed to meet weight regulations. In these cases, trucks are likely to need to use high-power charging throughout the day to satisfy energy requirements. It is assumed that once the vehicle's battery charge is depleted, any additional electricity

would be delivered by high-power charging (for example, if a vehicle requires 1 000 kWh to meet daily range requirements but has a maximum (effective) battery size of 700 kWh, then an additional 300 kWh would need to be sourced from a high-power charger). High-power charging is assumed to cost more than default charging at a depot, explained in further detail below. As battery-energy density improves over time, a lower share of high-power charging is required.

FCEVs are assumed to make use of a 70-kWh battery for all vehicle types. ERSVs are assumed to have sufficient battery capacity to have 150 km of range, which, according to Abid et al. (2021), would be sufficient to cover the distances required between main ERS corridors on motorways and final destinations.

Vehicle purchase cost

Vehicle purchase costs (CAPEX) for conventional vehicles are shown in Figure A. The purchase costs for ZEVs, and how they evolve in the future, are calculated based on cost estimates of batteries, vehicle glider (chassis), powertrain and subcomponents for each vehicle group, explained in greater detail in the following sections.

Battery costs

Battery cost reductions are assumed to be exogenous to the uptake of BEV HDVs, given the far larger market developing for passenger cars than HDVs. BNEF (2021a) estimate that average sales-weighted costs of lithium-ion battery packs globally in the year 2020 were EUR 122/kWh. Large battery cost reductions in the past decade have been primarily driven by economies of scale. There remain many opportunities to further reduce the costs of batteries with further increases in the scale of production, advanced manufacturing techniques and improvements in battery chemistries. The lower bound of future average battery prices chosen in this analysis sees cost reductions with average prices reaching EUR 70/kWh by 2030, in line with publicly stated ambitions by Ford and Renault (BNEF, 2021a) and reaching EUR 50/kWh by 2050. This is a relatively moderate decline compared to average annual reductions of 18.5% between 2013 and 2021. However, it is uncertain whether the learning rates observed historically will continue in the future. The share of raw material costs in the price of batteries is increasing, reaching approximately 80% in 2020 (BNEF, 2021a). Furthermore, high demand with relatively constrained supply in the short term means achieving similar rates of cost reductions may be challenging. The upper bound sees battery pack costs increase to reach EUR 150/kWh by 2025, similar to recent industry announcements pointing to short-term cost increases until new raw material production sources are operational (Kim, 2022). Long-term battery pack costs in the upper bound are conservatively assumed to reach EUR 100/kWh by 2050. The range of uncertainty in the upper and lower bounds is shown in Figure 1-I.

Batteries for truck manufacturers have historically been more expensive than passenger car batteries, principally due to the limited market and volumes. This cost difference, or "mark-up", is likely to decrease over time with increases in the scale of production of BEV trucks. In this analysis, upper and lower bounds for the cost difference between HDV battery prices and global Li-ion battery prices are derived from Ricardo and ICCT (2021) for the 2020-2030 timeframe and further estimated until 2050, shown in Figure 1J. Therefore, the cost of batteries in ZEV trucks is calculated by multiplying global average battery pack prices in each year (Euro/kWh) by an HDV mark-up factor and the size of batteries (kWh) in each vehicle.

Fuel cell and hydrogen storage tank costs

Commercial FCEVs are currently produced at a small scale of approximately 3 000 per year (IEA, 2021a). Only a fraction are likely to be HDVs, likely for pilot projects and early-stage trials. This makes it challenging to understand the current and future costs of fuel cell powertrains for HDVs. There remains a significant degree of uncertainty in base year costs, how costs may reduce with increasing scale of production (learning curves) and future production levels.

The US DOE (2021b) estimates the average HDV fuel cell power system cost in 2020 to be approximately EUR 283/kWe when produced at 1 000 units per year. This cost includes adjustments to reflect a 25 000-hour lifetime via measures such as stack oversizing (US DOE, 2021b). The same US DOE study also includes an ambitious pathway to lower FCEV costs to approximately EUR 142/kWe by 2025 and EUR 70/kWe by 2030, assuming a production ramp-up to 100 000 units per year by 2030 and an ultimate goal of EUR 53/kWe (here assumed to be by 2050). The present analysis uses the US DOE scenario as the lower bound of HDV FCEV costs since most cost reductions are driven by the uncertain and relatively rapid increase in production volumes. The upper bound assumes fuel cell costs decrease in line with US DOE technical improvements in components but without the cost reductions associated with increasing production scale, dropping from EUR 283/kW in 2020 to EUR 208/kW in 2025, EUR 154/kW in 2030 and EUR 123/kW in 2050. It should be noted that US DOE fuel cell cost estimates are considerably lower than values quoted in a recent review by Ricardo and ICCT (2021), which are based in part on Ballard supplied costs for the Hydrail project (Metrolinx, 2018). The range of uncertainty for fuel cell system costs is presented in Figure 1E.

FCEV vehicles are assumed to have hydrogen storage tanks tailored to meet their range requirements (similarly to battery requirements for BEVs). The size of the hydrogen storage tank needed for each truck type is estimated by multiplying the fuel efficiency by range requirements of each truck type. Hydrogen storage system costs (expressed in Euro/kg) are sourced from (Ricardo and ICCT, 2021), extended to 2050 and presented in Figure 1G.

Electric road system vehicle pantograph costs

Pantograph costs are assumed to range between EUR 18 000 and EUR 28 000 in early-stage deployment (pre-2030) and are assumed to drop to between EUR 10 000 and EUR 12 000 in 2050 due to market scale-up based on estimates by the IEA (2017), Kühnel, Hacker and Görz (2018) and Ainalis, Thorne and Cebon (2020), as shown in Figure 1-O.

Powertrain costs

Ranges on the costs of electric drivetrain components are sourced from Ricardo and ICCT (2021). All ZEV technologies (BEV, ERSV and FCEV) are assumed to share similar electric powertrain components such as electric motors, inverters, high-voltage systems and on-board charging (excluding batteries, pantographs and fuel cells). This is a simplification, as there are likely to be differences in a number of components such as thermal management and high-voltage distribution systems. However, these are considered to be minor (<10% of costs) and are omitted to simplify the model. Upper and lower bound estimates of total electric drivetrain costs are shown in Figure 1D. The cost of a diesel engine is estimated according to equation 3 (in Annex B) used in Hunter et al. (2021) and assumed to be constant over time and applicable to all vehicle groups. Additional costs associated with meeting increasingly stringent air pollutant emissions regulations are not accounted for.

Glider costs

The cost of the vehicle excluding powertrain (also known as the vehicle glider) is estimated from median ICEV purchase costs (see Figure , left) for each vehicle group, minus the cost of the diesel powertrain calculated according to equation 3, and is assumed to be constant over time.

Residual value

The residual value of diesel trucks drops rapidly after first purchase, with upper and lower bounds of 35% and 20% of initial purchase cost after seven years respectively (calculated based on the interquartile range of the vehicle purchase costs shown in Figure A and second-hand vehicle sales data detailed in Annex B), shown in Figure 1P.

The residual value of ZEVs is highly uncertain. It is possible that the lower operation and maintenance requirements of ZEVs, due to their reduced mechanical complexity, could extend their maximum vehicle lifetime and increase residual value. The residual value of battery packs is influenced by battery degradation and the number of battery charging cycles over its lifetime. Cycle lifetimes are increasing over time and could further improve residual values. Conversely, the residual value of new technologies could be lower than that of conventional vehicles, at least initially for first-generation trucks, due to immature second-hand markets and unknown expectations about vehicle lifetimes. Neither of these effects is explicitly modelled but would be a valuable addition in future work.

ZEVs are assumed to show similar market dynamics to diesel vehicles with residual values after seven years ranging between 20-35% of the sum of vehicle glider, powertrain, fuel cell, hydrogen fuel tank and pantograph costs and with respect to the cost of a new vehicle in the year that vehicle ownership ends (for example the residual value of a model year 2020 vehicle reaching end of ownership in 2027 would be between 20-35% of the cost of a model year 2027 vehicle). Vehicle battery packs are assumed to have between 5% and 20% residual value after seven years (again with respect to a new equivalent battery pack).

Vehicle operational costs

Vehicle operational costs (OPEX) are a major factor in the total cost of ownership and include energy costs (diesel fuel, hydrogen and/or electricity) and operation and maintenance costs.

Diesel costs

Estimates for future uncertainty of diesel prices are based on historical variance over the past decade in Europe. As users of fuel for commercial operations, road freight companies are typically able to receive a rebate on value added tax (VAT) paid on fuel and electricity. Fuel prices and excise duties are sourced from OECD (2020), average diesel fuel prices in Europe between 2010 and 2019 varied between EUR 0.95/Litre and EUR 1.50/Litre excluding VAT and other recoverable taxes. These are used as upper and lower bounds to assess in the future.

Electricity costs

Base electricity price data for non-household consumers in Europe, excluding VAT and other recoverable taxes and levies are sourced from (EUROSTAT, 2022) (Band IC: 500 MWh-2 000 MWh). There is significant

variance in electricity costs between countries, for simplicity this analysis assumes an average electricity cost of EUR 0.125/kWh in line with EU averages in 2020.

Future electricity costs are uncertain. The increasing adoption of renewable electricity generation is likely to reduce costs on average, although a number of other factors may limit this effect. A range of future base electricity costs are examined in this analysis to account for this uncertainty and are shown in Figure 1A. In the lower bound, electricity costs are assumed to decrease by 2% every year from 2020 values leading to a decrease of approximately 50% by 2050. In the upper bound, electricity costs are assumed unchanged from the base year.

The cost paid by an electric truck (BEV or ERSV) per unit of electricity is estimated as the sum of base electricity costs and an additional cost needed to pay off infrastructure investments such as chargers, overhead catenary wires and grid connection costs, shown in Figure 9. Infrastructure costs associated with charging are expected to be dominated by the cost of chargers. A study by Burges and Kippelt (2021) estimated that grid connection and other infrastructure costs are expected to account for just 10% of charging infrastructure costs. Depot charging costs are particularly dependent on assumptions of the required payback periods and the assumed utilisation. Basma, Saboori and Rodríguez (2021) estimate depot charging costs to be approximately EUR 0.03/kWh for a 100 kW charger and assuming eight hours of use per day. Burges and Kippelt (2021) estimate just under EUR 0.05/kWh for a similar concept including grid infrastructure costs. In this analysis, a range of depot charging costs between EUR 0.03-0.06/kWh is used to account for uncertainty in operations and infrastructure costs. When added to base electricity costs (EUR 0.125/kWh in 2020), these give the total cost per unit of electricity for a truck using depot charging. The costs associated with high-power charging on motorways and ERS are more uncertain and are explained in the following sections.

Figure 9. Electricity costs for battery electric vehicles and electric road system vehicles
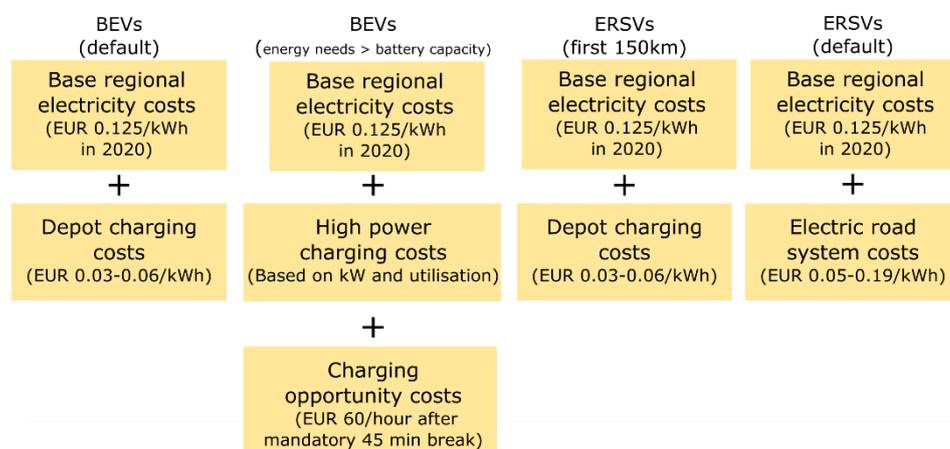
BEV high-power charging costs and opportunity costs

BEVs are assumed to use depot charging by default due to its lower cost and the fact that vehicles can be charged overnight when not in use. However, when vehicles have limited battery capacity due to gross weight limits (as explained above) a share of the electricity consumption will have to be sourced from high-power charging (see equation 6 in Annex B).

High-power charging infrastructure for trucks would be necessary for vehicles to recharge in a service station on a main road in a reasonable time without incurring significant additional logistical costs. There are currently proposals for standards enabling HDV chargers with power ratings around one megawatt. However, the installation of the required infrastructure will not be immediate. There is currently limited charging infrastructure dedicated to BEV trucks available on main roads and its future availability is uncertain. To account for this uncertainty, a conservative lower bound scenario sees the average power rating of high-power chargers on main roads rise from 20 kW in 2020, to 50 kW by 2025, 100 kW by 2030 and 1 000 kW by 2050. A more ambitious upper bound scenario sees average power ratings hit 500 kW by 2025 and 1 000 kW by 2030. This range of uncertainty is shown in Figure 1L.

The cost of charging infrastructure and its use are also uncertain. The cost of chargers are assumed to vary between EUR 1 000 to EUR 3 000 for a 20 kW charging station, EUR 50 000 to EUR 70 000 for a 100 kW, EUR 170 000 to EUR 240 000 for a 350 kW charging station and EUR 300 000 to EUR 700 000 for a one-megawatt charging station based on literature estimates (Basma, Saboori and Rodríguez, 2021; Burges and Kippelt, 2021). These costs are included in charging costs per kWh and are estimated according to equation 5 for both upper and lower bounds and shown in Figure 1M. High power charging costs are highly dependent upon the number of hours each charger is used each day, as shown in Figure 9 right, which shows the cost of a 1 MW charger as a function of the hours of use per day. High-power public chargers are assumed to be used between three and six hours per day to account for uncertainty in their utilisation. The cost per kWh of high-power charging is therefore a function of the average rated power in any given year of the charger (Figure 1L) and the associated cost per kWh accounting for its utilisation (Figure 1M).

Furthermore, additional time spent charging is likely to incur significant opportunity costs upon truck operators if it increases journey times. This can be partly mitigated by charging during mandatory drive rest periods (45 minutes every 4.5 hours of driving in Europe). Median truck driver wages in 2020 in the United States were approximately EUR 19/hour and are assumed to be similar in Europe (Bureau of Labor Statistics, 2020). Median TCO of large BEVs is roughly EUR 520 000 over seven years for an estimated 2 700 hours per year, meaning earnings have to be at least EUR 52/hour simply to cover driver wages and truck lifetime costs. Charging opportunity costs are therefore set at EUR 60/hour after the first 45 minutes of driver rest period. This is converted into a cost per kWh in each year by dividing by the rated power of chargers (Figure 1L). For a 20 kW charger, this equates to a cost of EUR 3/kWh, which is likely financially unfeasible for most operations. However, opportunity costs drop to EUR 0.06/kWh when using a highly utilised one-megawatt charger. The total cost per kWh associated with the use of high-power charging in any given year is therefore the sum of base electricity costs, high-power charging costs and opportunity costs as shown in Figure 9.

ERS usage costs

The adoption of an ERS would require building overhead lines on main arterial roads. Electrifying the busiest motorways would cover the majority of HDV vehicle travel. In the United Kingdom, for example, 7 230 km (4 519 miles) of motorways and main roads (approximately 2.4% of the total national road network) carried 68% of national HDV road traffic in 2019 (UK DfT, 2020). Similar estimates for Germany show 60% of HDV tonne kilometres are carried on the most intensively used 3 966 km of motorways (Wietschel et al., 2019). There are economies of scale in the size and spread of the network of ERS up to a threshold, above which further expansion of the network yields marginally lower benefits due to lower traffic (Borjesson, Johansson and Kågeson, 2021).

Literature estimates of the cost of an ERS range between EUR 1.1-1.65 million per kilometre and direction (Wietschel et al., 2019; Ainalis, Thorne and Cebon, 2020; Hacker, 2020; Movares, 2020). This is a significant

investment but, in the context of road infrastructure, is not extreme. Hacker (2020) put the cost of covering 4 000 km of motorways in Germany with overhead ERS at approximately EUR 12.2 billion, equivalent to approximately 18% of truck toll revenues over a 15-year period of construction. ERS infrastructure costs can be reduced by installing an intermittent overhead line system, avoiding particularly challenging and expensive stretches of road (e.g. tunnels, bridges), this would require pantograph systems that are retractable, such as those developed by Siemens (2020).

Table 5. Electric road system infrastructure cost uncertainty bounds

Bound	Infrastructure costs (per lane-km)	Share of trucks using ERS	Usage cost per km	Cost per kWh*
Lower	1.1 million	70%	EUR 0.08	EUR 0.05
Upper	1.65 million	32%	EUR 0.28	EUR 0.19

Note: Assuming mean 3 400 vehicles/day in a single direction and average truck energy efficiency of 1.5 kWh/km and a 35-year payback period.
*Cost per kWh purely to payback infrastructure costs and excluding base electricity costs.

The present analysis aims to account for the uncertainty in ERS construction costs as well as accounting for uncertainty in the utilisation of the ERS infrastructure, as shown in Table 5. The financial feasibility of an ERS is influenced by the daily flow rates of trucks on the road and the share of those trucks using the ERS. If ERS-capable trucks entered the mass market in 2030 and reached 100% of new vehicle sales by 2040, the average utilisation of an ERS built in 2030 over a 35-year asset life, accounting for the turnover of the vehicle fleet, would be approximately 70% if all trucks used the ERS. If instead ERS-capable trucks only reached 50% market share by 2045, then the average utilisation would be just 32%.

Figure 10. The effects of utilisation on electric road systems and high-power charging costs
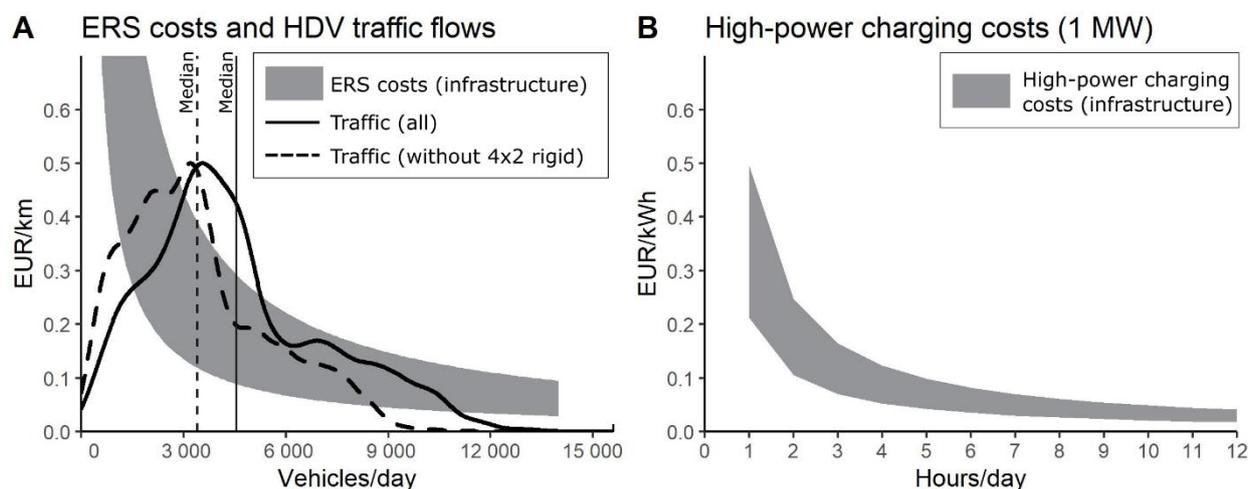
Notes: ERS: electric road system; HDV: heavy-duty vehicle; MW: megawatt.
A: Range shows how ERS usage costs per km change based on vehicle flow rates (needed to payback infrastructure investments and excluding electricity costs). The lower bound of the range assumes ERS infrastructure costs to be EUR 1.1 million/lane-km with high utilisation of 70% of trucks using the ERS over a 35 year timeframe. The upper bound assumes EUR 1.65 million/lane-km and low utilisation of 32%. Heavy-duty vehicle traffic flow (per direction) histograms on motorways sourced from (UK DfT, 2022).
B: High-power charging costs, a one-megawatt charger is assumed to cost EUR 300 000 lower bound and EUR 700 000 upper bound.

The cost per kilometre for each truck needed to ensure payback of the construction of an ERS is calculated using equation 7 in Annex B and shown in Figure . Figure includes a distribution of annual average daily flow rates of heavy-duty freight vehicles on all sections of motorways in Great Britain (weighted by their length) to illustrate typical traffic volumes on roads where an ERS might be built (UK DfT, 2022). Also shown is the same distribution omitting rigid 4x2 vehicles, in case either their smaller size means that a pantograph is not appropriate or a large battery BEV solution is preferable.

Average costs for ERS payback and use are between EUR 0.08 per vehicle km and EUR 0.28 per vehicle km assuming flow rates of 3 400 vehicles in a single direction/day (the mean excluding 4x2 rigid trucks). These costs are assumed to be transferred to truck operators as an additional cost per kWh of electricity consumed when using the ERS and are estimated by dividing costs per kilometre by the average energy efficiency of a BEV truck fleet (~1.5 kWh/km). Upper and lower bounds for ERS costs, accounting for uncertainty in infrastructure construction costs and its utilisation are therefore EUR 0.19/kWh and EUR 0.05/kWh respectively (excluding base electricity cost). These are assumed to be constant over time and are shown in Figure 1N. It is assumed that ERSVs use depot charging to supply the energy needed to cover the distance to and from an ERS on main roads (here, assumed to be 150 km). All further electricity needed to meet average daily range requirements is assumed to come from overhead catenary wires. For example, if a vehicle has a 400-km range requirement, energy needs for 150 km are priced at low depot charging costs and the remaining 250 km of energy needs are priced at higher ERS costs.

Hydrogen costs

This analysis uses a broad range of uncertainty for hydrogen price projections. Specific detail on hydrogen production routes are not considered for simplicity. Hydrogen prices in the base year are estimated at EUR 9.50/kg based on current average prices available at the pump in Europe (H2live, 2022). Hydrogen is currently mainly produced by steam methane reformation (IEA, 2019). Moving to low-carbon hydrogen production would increase the cost in the short term. Hydrogen is also typically dispensed at 350 bar; refuelling stations for heavy-duty vehicles would likely need to operate at 700 bar or with liquid hydrogen. They would also require larger hydrogen storage capacities than are currently available (Rose, 2020). These are all factors that would increase costs in the short term. Conversely, the increasing adoption of heavy-duty hydrogen vehicles and higher utilisation of refuelling infrastructure would reduce hydrogen costs at the pump in the longer term. Relatively expensive tube trailers would likely be used for hydrogen distribution initially with low demand for hydrogen. As demand for hydrogen refuelling grows, liquid hydrogen trucks and pipelines may become more feasible with lower associated costs (Yang and Ogden, 2007).

A cost optimisation model developed by Rose (2020) for HDV hydrogen refuelling stations in Germany estimated hydrogen costs of between EUR 5.50-6.50/kg assuming highly utilised infrastructure in 2050, an FCEV share in the total truck fleet above 60%, reductions in costs from grid balancing and with hydrogen produced via electrolysis and electricity at EUR 0.10/kWh (lower than the base year assumed for electricity in this analysis), broadly similar to past literature estimates. The analysis by (Rose, 2020) also highlights that the cost of hydrogen at the pump would increase significantly with lower FCEV shares in the total vehicle fleet since a minimum number of hydrogen refuelling stations would be required in the motorway network. With a 40% FCEV share of the vehicle fleet, the hydrogen cost would be approximately EUR 8.1/kg. The upper bound used in this analysis assumes hydrogen prices will reduce from EUR 9.5/kg in 2020 to reach EUR 8.1/kg in 2050. In an ambitious lower bound, assuming very low hydrogen production costs and high utilisation, hydrogen costs at the pump are assumed to reach EUR 1.5/kg by 2050, similar to optimistic estimates by Zhou and Searle (2022) and likely requiring significant government subsidies.

Operation and maintenance costs and vehicle financing costs

Hunter et al. (2021) conducted a comprehensive review of truck operation and maintenance (O&M) costs between different powertrain types and categories of vehicles. They highlighted that the reduced mechanical complexity of BEVs leads to O&M costs that are approximately a third lower than conventional diesel equivalents. Informed by Hunter et al. (2021), estimates for American class 4, class 8 and buses, O&M costs in this analysis are assumed to be EUR 0.74/km for diesel and FCEV vehicles and EUR 0.47/km for BEVs. ERS vehicles are assumed to have the same O&M costs as BEVs since O&M costs associated with the upkeep of overhead catenary wires and high power charging systems are included in electricity costs for each type of vehicle. O&M costs are assumed constant over time and between vehicle types for simplicity.

Purchasing a truck is likely to have additional financing costs that must be paid off over the lifetime of the vehicle. These are estimated according to equation 4 in Annex B. All TCO estimates assume a 10% discount rate and are quoted in 2020 prices.

Uncertainty allocation

Uncertainty is allocated to a number of input variables and its impact on TCO is estimated by randomly sampling input values for each variable over a number of iterations (Montecarlo methods). This uncertainty is implemented in one of two ways:

1. For variables with uncertainty that are assumed to be constant over time, the variable in each iteration (i) is calculated using the following formula:

$$x_i = x_{lb} + U_i(x_{ub} - x_{lb})$$

2. For variables with uncertainty that change over time, the variable in each iteration (i) is calculated using the following formula:

$$x_{i,yr} = x_{lb,yr} + U_i(x_{ub,yr} - x_{lb,yr})$$

Where U_i is a randomly sampled value from a uniform distribution between 0 and 1 for each iteration and each variable with uncertainty. Subscripts ub and lb denote upper and lower bounds respectively.

Limitations

Like all models, there are a number of limitations and caveats. This analysis does not explore the following:

1. This analysis assumes battery and hydrogen storage capacity can be modular and designed to meet specific range requirements. This assumes that vehicle fleets can be used relatively flexibly, with short-range applications serviced by vehicles with relatively small batteries or hydrogen fuel tanks, and longer-distance applications serviced by appropriately specified vehicles.

2. This analysis only considers low-power depot charging and en-route public fast charging. It does not consider warehouse charging taking place during deliveries where vehicles could potentially avoid any opportunity costs. These could help to reduce BEV battery size requirements.

3. This analysis accounts for battery weight limitations to avoid reduced payload and arbitrarily sets a maximum possible battery size of one megawatt hour. However, it does not consider volume constraints to batteries or hydrogen fuel tanks, or limitations to their installation on vehicles.

4. This analysis assumes all input variables in Figure 1 are independent. This is a simplification. The most significant limitation this raises is that electricity costs and hydrogen costs are considered independent from each other when in reality, low (green) hydrogen prices are likely to require cheap electricity to be feasible.

5. This analysis does not explicitly account for vehicle production and manufacturing costs and how they might be reduced with economies of scale.

6. This analysis also does not account for possible revenues or discounted electricity costs from BEVs providing grid flexibility services such as demand management and vehicle-to-grid charging. It also does not account for wider system costs such as changes in the electricity price due to additional peak demand produced by HDV charging.

7. This analysis explores a wide range of vehicle groups and different range requirements and annual mileage within each group. However, it does not consider additional detail on specific use cases or machinery operated by vehicles e.g. refrigeration, crane or lift equipment.

8. It is assumed that the market shares of different truck categories and their operational requirements remain constant over time.

Annex B. Equations and descriptions

#	Equation	Description
1	$$TCO_{MY,P} = CAPEX_{Yr=MY,P}$$ $$-Residual_{Yr=L,P}$$ $$+ \sum_{Yr=MY}^{MY+L} OPEX_{MY,Yr,P}$$	The TCO of a vehicle with powertrain P produced in model year MY and with lifetime L.
2	$$Efficiency_{Yr} = Efficiency_{Age=0} \times \frac{1}{1 - (Age \times \frac{0.2}{25000/2700})}$$	Fuel efficiency (MJ/km) degradation of FCEVs due to catalyst poisoning is estimated in line with DOE future targets of 20% reduction in fuel economy after 25 000 hours of operation (US DOE, 2021b) and assuming 2 700 hours of vehicle use per year.
3	Engine cost (USD) = 7617 + 15.1*EnginePowerkW+0.1* EnginePowerkW^2	The cost of a diesel engine is estimated according to the equation used in Hunter et al. (2021).
4	PMT(Int, AL, CAPEX) = (Int x CAPEX(1-Int)^AL)/(1-(1+Int)^AL)	Payment of a loan. "Int" is the Interest rate, "CAPEX" is the capital expenditure, "AL" is the asset life.
5	High power charging cost $$EUR/kW = \frac{O\&M * CAPEX - PMT(Int, AL, CAPEX)}{Daily\ Hours * 365 * Power\ Rating}$$	High power charging costs. "Int" is the Interest rate, assumed to be 3%; "CAPEX" is the cost per charging point (here assumed to be EUR 300 000 lower bound, EUR 1M upper bound); "O&M" are annual operational and maintenance costs, expressed as a share of CAPEX and here assumed to be 4%; "AL" is the asset life, assumed to be five years; "Daily Hours" is the number of hours per day that the charger is in use; "Power rating" is assumed to be 1 000 kW.
6	If $E_{Range\ requirement}$ <= Max effective battery capacity, then the high power charging share is equal to zero. If $E_{Range\ requirement}$ > Max effective battery capacity, then the high power charging share is: $$Share\ \% = \frac{E_{Range\ requirement}}{Max\ effective\ battery\ capacity} - 1$$	The share of BEV's electricity consumption from high power chargers (rather than depot charging). Where $E_{Range\ requirement}$ is the energy required to meet a truck's daily range requirements.
7	ERS cost per kilometre: $$EUR/km = \frac{O\&M * CAPEX - PMT(Int, AL, CAPEX)}{Daily\ Flow * Utilisation * 365}$$	The cost of using a catenary electric road system on motorways and high-traffic main roads. "Int" is the Interest rate, assumed to be 3%; "CAPEX" is the cost per km of building the ERS (here assumed to be EUR 1M/km lower bound, EUR 3M/km upper bound); "O&M" are annual operational and maintenance costs, expressed as a share of CAPEX and here assumed to be 2%; "AL" is the asset life, assumed to be 35 years; "Daily Flow" is the number of heavy-duty trucks that flow over each km of motorway per day; "Utilisation" is the share of trucks that use the ERS infrastructure.

Decarbonising Europe's Trucks
How to Minimise Cost Uncertainty

Trucks account for one-fifth of transport sector emissions in Europe. To decarbonise, heavy-duty road freight must switch to zero-emission vehicles quickly. This report examines whether battery electric vehicles, electric road systems and hydrogen fuel cell vehicles could compete with diesel-driven vehicles. It looks at the total cost of ownership across nine different vehicle-size segments in Europe. The report gives six recommendations to accelerate the transition to zero-emission trucks, including the provision of necessary infrastructure.